Ultraviolet Radiation

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225

To my associates in

THE GENERAL ELECTRIC COMPANY

Preface

There is a great wealth of information available in the scientific and technical literature covering every aspect of ultraviolet radiation. However, it is often very difficult for the nonspecialist in the field of radiation to find the information he requires. This book is intended to answer some of the questions which confront physicists and specialists in fields other than physics when they find it necessary to work in this portion of the spectrum. Its preparation was prompted by many inquiries from physicists, biologists, medical men, chemists, engineers, and laymen over the course of the years.

It does not make the slightest pretence at being comprehensive or all-inclusive, but merely treats of those matters which seem to me to have been of most importance to people who are attempting to utilize radiation at the short-wave end of the spectrum.

It has been necessary to describe various commercial arcs. These have been selected in general as illustrative of certain types of discharges. A catalog of lamps was not intended. Obviously such a catalog would rapidly become obsolete, and this kind of information can readily be obtained from the many reputable manufacturers. However, it was my thought that the descriptions given would be of some help in guiding the user in the proper direction.

The chapters on reflection and transmission obviously do not cover the performance of all materials but, for the most part, only of those which are commonly used and readily available.

The section on applications is limited to those which have interested me most and in which certain basic principles are involved.

Acknowledgments

I wish to acknowledge my debt to my associates in the General Electric Company for the help which I have had from them. Particularly Dr. L. Apker, Dr. L. Buttolph, Dr. J. D. Cobine, Mr. C. G. Found, Dr. N. T. Gordon, Dr. P. D. Johnson, Mr. E. B. Noel, and Dr. F. J. Studer who read parts of the manuscript. I am indebted to Dr. Studer for the photographs of the spectra in Fig. 4 and to Miss Jeanette Cooper for the photographs of the cathodes in Fig. 7. The National Carbon Company contributed the photographs of arcs in Fig. 30 and the Hanovia Company those in Figs. 9, 11, and 27.

I am also indebted to the Editors of the *Physical Review,* the *Journal of Applied Physics,* the *Journal of the Optical Society, Illuminating Engineering,* the *Transactions of the Electrochemical Society,* the *Journal of the American Ceramic Society,* Bureau of Standards' *Journal of Research* and Van Nostrand and Company for permission to reproduce illustrations from their publications.

I am particularly grateful to Miss G. Feola for her painstaking assistance in preparing the manuscript.

LEWIS R. KOLLER

Schenectady
April 7, 1952

Contents

1. Introduction 1

2. Arcs 20

3. Incandescent Sources of Radiation 90

4. Solar Radiation 106

5. Transmission 140

6. Reflection 178

7. Some Applications and Effects of Ultraviolet 196

8. Detectors of Ultraviolet Radiation 237

Index 263

1 Introduction

Discovery of Ultraviolet

In 1666 Isaac Newton allowed a sunbeam to enter a darkened room through a small hole in a shutter, pass through a prism, and fall upon the opposite wall. The spectrum of "very vivid and intense colors" which he observed "was at first a very pleasing divertisement." By means of further experiments he was able to prove that white light was made up of several components. Once this fact was established, the way was opened for the investigation of the properties of these components.

In one of these investigations, Sir William Herschel in 1800 discovered that the solar spectrum extended out beyond the portion which was visible to the human eye. He formed a spectrum and passed a thermometer through the various colors and compared the reading with that of a similar thermometer shaded from the spectrum. He found a rise in temperature as he passed from the violet to the red end. But still more astounding was the fact that the thermometer showed a higher temperature in the dark space beyond the red than it did in any part of the visible spectrum. This meant that there was some intense radiation beyond the region which was visible to the eye. This invisible radiation beyond the red end of the spectrum is now known as infrared radiation.

In 1801 J. W. Ritter investigated the other end of the spectrum and showed that chemical action was caused by some form of energy in the dark portion beyond the violet, the region which is now called the ultraviolet. He studied this portion of the spectrum by observing the blackening of silver chloride which is decomposed by light. He found that, when it was exposed to radiation in the region beyond the violet, it was decomposed even more rapidly than by radiation in the visible part of the spectrum. Thus Herschel and Ritter demonstrated that there was radiant energy at both ends of the spectrum beyond that part which the eye could see.

In 1804 Thomas Young showed that the invisible chemically active

radiations beyond the violet end of the spectrum (subsequently called actinic rays) were subject to the laws of interference. He projected the interference pattern known as Newton's rings upon paper treated with silver chloride. By means of the blackening of the silver chloride he observed not only the rings made by the visible light but also a system of rings of smaller diameter. These corresponded to some radiation of shorter wavelength than visible light. This observation, together with the work of many subsequent investigators, established the fact that the visible effects, the ultraviolet effects, and the infrared effects were all manifestations of the same kind of electromagnetic radiation, differing from each other only in frequency. There is in reality no sharp dividing line between these forms of radiant energy. Nor is there one between these and the X-rays and gamma rays which were discovered later. It is convenient, however, to separate these forms into distinct groups because of the nature of the physical and biological effects which they produce and because of the special techniques required for their production, detection, and measurement.

Sources of Ultraviolet

The sources of ultraviolet may be divided into two classes: natural and artificial. There is only one natural source of any importance, the sun. The artificial sources comprise a wide variety of arcs and incandescent lamps. The details of these various sources are discussed in Chapters 2, 3, 4.

Wavelength Units

In discussing ultraviolet radiation it is necessary to describe it both quantitatively and qualitatively. Since it consists of electromagnetic waves, it may be described qualitatively by stating its wavelength. The unit of wavelength most commonly used is the one used for visible light, namely, the Angstrom unit which is equal to 10^{-8} cm. Occasionally, wavelengths are expressed in microns which are thousandths of a millimeter, or more often in millimicrons which are thousandths of a micron. These units with their metric equivalents are given in Table 1.

TABLE 1

Wavelength Units and Their Metric Equivalents

Unit	Symbol	Metric Equivalent, cm
Angstrom	A	10^{-8}
Micron	μ	10^{-4}
Millimicron	mμ	10^{-7}

Thus a wavelength of 4000×10^{-8} cm would be expressed in the various units as 4000 A, 0.4 μ, or 400 mμ.

The frequency of a vibration is really a more fundamental quantity than its wavelength, but the wavelength is the quantity which is determined directly by experiment and is more commonly used. The frequency and wavelength of radiation are related by the equation

$$c = n\lambda$$

where c = the velocity of light, namely, 3×10^{10} cm per sec (in free space).
n = the frequency of vibration in vibrations per second.
λ = the wavelength in centimeters.

Definition

Ultraviolet radiation is usually defined as electromagnetic radiation of wavelength between 40 and 4000 A. It bridges the gap between the longest wavelength X-rays and the shortest wavelengths of light visible to the human eye. The term originally designated any radiation of shorter wavelength than the visible violet. This was before the discovery of X-rays. After their discovery it became necessary to set a lower limit as well as an upper limit to the ultraviolet.

Figure 1 shows in schematic form the wavelength limits of the visible and ultraviolet spectrum. When shown in this form, the X-ray and gamma ray regions are compressed. A frequency plot would emphasize the tremendous range covered by these radiations.

The limits of the visible spectrum are not very sharply defined. They vary somewhat from one individual to another. If the limits are set as the wavelengths at which the eye sensitivity is 1/100,000 of its maximum value, they would be 3760 A and 7880 A, respectively. The International Commission on Illumination defines visible radiation for practical purposes as the range of wavelengths between 3800 and 7800 A.

The ultraviolet spectrum is somewhat loosely divided into the near and the far ultraviolet regions. These comprise the regions between the wavelengths 4000 and 3000 A and 3000 and 2000 A, respectively. The former includes the wavelengths found in solar ultraviolet (as observed at the surface of the earth).

The region between 2000 and 40 A is called the extreme ultraviolet. Since radiation in this wavelength region is strongly absorbed by air, it is necessary to place apparatus used in its study in a vacuum or in a

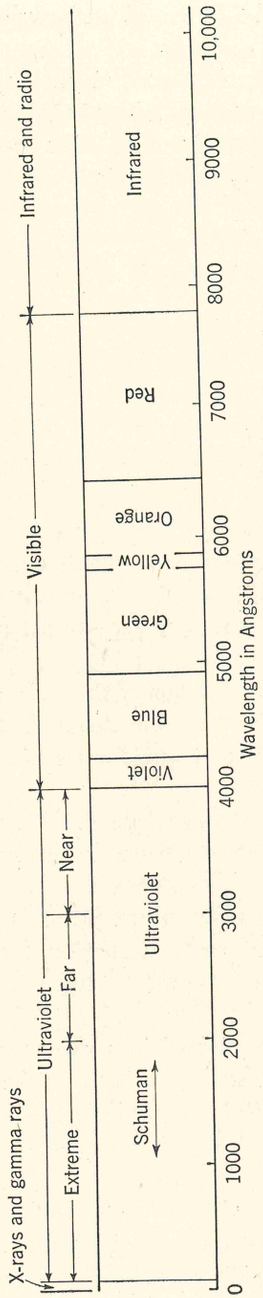

FIG. 1. The electromagnetic spectrum.

gas which does not absorb ultraviolet. Hence this region is also called the vacuum ultraviolet.

The region from 1850 to 1200 A is called the Schuman region after V. Schuman who was the first to investigate it.*

Ultraviolet is not a single entity but is a very wide band of wavelengths. This is a fact which is often not realized. The ultraviolet spectrum covers a range of a hundredfold in wavelength, whereas the visible range of wavelengths is only twofold. The difference between blue and red light is quite insignificant compared with the differences between the extremes of the ultraviolet spectrum.

THE EYE

The human eye is not equally sensitive to all colors, or rather wavelengths of light. Figure 2 shows the relation between wavelength and visual sensitivity for the *average* eye. This is known as the visibility curve. It shows the relative sensation of brightness produced upon the average eye by equal amounts of energy throughout the spectrum. The curve shows a maximum at a wavelength of 5550 A and falls to very low values in the violet and in the red. This means that a given amount of energy of wavelength 5550 A falling upon the retina produces a greater sensation of brightness than an equal amount of energy at any other longer or shorter wavelength. The peak at 5550 A coincides closely with the peak of the solar energy distribution

* In the German literature on ultraviolet therapy the spectrum is divided into the following ranges: UV *A*, 400–315 mμ; UV *B*, 315–280 mμ; UV *C*, below 280 mμ.

curve. In the course of evolution the eye appears to have developed so that it uses most efficiently the kind of radiation which predominates in the solar spectrum.

The definition of ultraviolet is based largely on the limitations of the human eye. No two persons' eyes are exactly alike, and so the actual dividing line between visible and invisible radiation is not exactly the same for all observers. In general radiation in the wavelength range

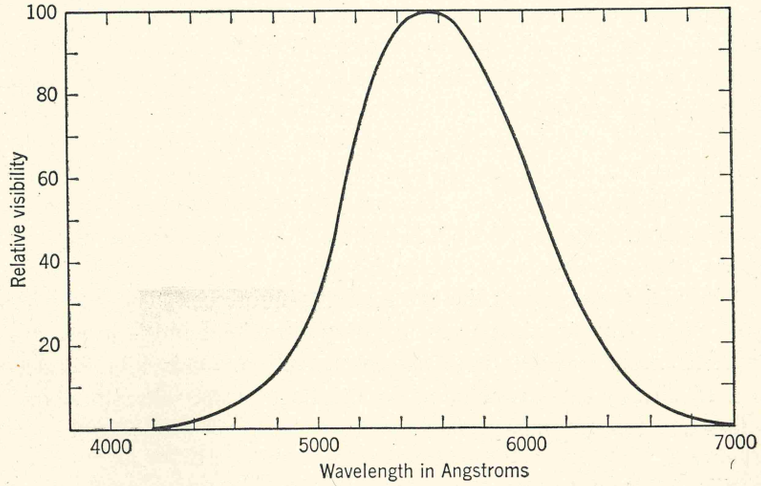

FIG. 2. Relative visibility curve for the average human eye.

between 7600 and 3800 A penetrates the eye to the retina and is perceived as light. Young people with normal sight can see as far into the ultraviolet as 3130 A. The visual sensation produced by radiation in this region, however, is not violet but blue. A wavelength 3076 A appears to be beyond the range for even the most sensitive eyes.[1] With advancing age, the ability to see beyond 3800 A is lost.

The response to ultraviolet falls off very rapidly with wavelength. That is, the ultraviolet end of the visibility curve is very steep. For a group of people tested by deGroot,[2] the sensitivity to 3650 A was at most 1.5 per cent of that to 4047 A, and the sensitivity to 3130 A was ½ per cent of that to 4047 A.

The ultraviolet incident on the eye is absorbed successively by the cornea, the aqueous humor, the lens, and the vitreous humor before reaching the retina. The relative absorption in these various parts differs. It is greatest in the lens, next in the cornea, then in the vitreous

humor, and least in the aqueous humor. It is the increasing absorption in the lens with increasing age which is chiefly responsible for the inability of older persons to see in the ultraviolet. The lens transmits about 15 per cent at 4050 A and 0.1 per cent at 3650 A. The receptors of the retina (the rods and cones) are actually quite sensitive to ultraviolet if it is permitted to reach them. The removal of the lens as in cataract operation removes the strongest absorbing medium in the eye for ultraviolet and permits more of it to reach the retina. Consequently, persons who have had a cataract operation and have had the lens removed are able to see shorter wavelengths in the ultraviolet than persons with normal vision. In these cases, the rod or cone * vision is about $\frac{1}{30}$ as sensitive at 3650 A as at the maximum of the visibility curve, instead of being negligible as in the normal eye. At this wavelength, the rods are as sensitive as in yellow light and the cones are as sensitive as in the near red. The average sensitivity of the aphakic eye (eye without lens) at 3650 A is about 1000 times that of the normal eye.[3]

Ultraviolet also causes the eye media to fluoresce. The fluorescence is of longer wavelength than the exciting ultraviolet and is in the visible spectrum and so is able to stimulate the retina. It is sometimes difficult to distinguish between the direct effect of the ultraviolet on the retina and this secondary effect.

Penetration

One of the many important differences between the characteristics of radiation in different spectral regions is the depth of penetration. Table 2 gives the values for the depth of penetration into skin of a significant amount of different kinds of incident radiation. The table shows that the penetration of ultraviolet into the skin is considerably less than that of infrared. However, even within the ultraviolet range there are tenfold differences. Penetration is discussed in greater detail in Chapter 5 on Transmission.

Physical Units

The quantity of radiation may be expressed in terms of any one of a number of different physical or biological units, depending upon which aspects of radiation are under consideration. The physical units relate to work or energy; the biological ones, to the effects which the radia-

* The rods are the receptors which function in dim light. The cones are the receptors which function in bright light and are the organs of color vision.

TABLE 2

Penetration of Radiation into the Human Skin *

Spectral Region	Penetration in Millimeters
Far ultraviolet	Superficial
1800–2900 A	0.01–0.1
Near ultraviolet	Superficial
2900–3900 A	0.1–1
Visible spectrum	Deep
3900–7600 A	1–10
Near infrared	Deep
7600–15,000 A	10–1
Far infrared	Superficial
15,000–150,000	1–0.05

* Coblentz, W. W., *J. Am. Med. Assoc.*, **132**, 378 (1946).

tion produces. Obviously, large units such as horsepower would not be suitable for this purpose, and the ones most commonly used are the watt-second, the calorie, and the erg. These three units are measures of total *quantity of energy* or work. The *time rates* at which this energy is received or emitted in the corresponding units are the watt, the calorie per second, or the erg per second.

The intensity or energy density of the radiation is often important, as well as the total quantity. This is expressed in terms of the energy incident upon a unit area or absorbed in a unit volume; for example, watts per square centimeter or watts per cubic centimeter.

According to the quantum theory, radiant energy occurs in discrete units or quanta. The energy of each of these fundamental units is related to its frequency by the relation

$$E = h\nu = hc/\lambda$$

where E is the energy of a single quantum in ergs.
h is Planck's constant 6.62×10^{-27} erg sec.
c is the velocity of light 3×10^{10} cm per sec.
ν is the frequency of the radiation per second.
λ is the wavelength of the radiation in centimeters.

This unit of energy, the energy per quantum, is a very small one for most purposes but is included here because in many phenomena it is significant.

In photochemistry a unit called the Einstein is used. The Einstein is the energy absorbed when each molecule of a gram-molecular weight

absorbs 1 quantum of radiation. This is $Nh\nu$, where N is Avogadro's number 6.06×10^{23}, the number of molecules per gram molecule.

These units and their cgs equivalents are given in Table 3.

TABLE 3

PHYSICAL UNITS AND THEIR CGS EQUIVALENTS

Unit	Symbol or Abbreviation	cgs Equivalent in Ergs
Watt-second (joule)	w-sec	10^7
Calorie	cal	4.2×10^7
Erg	....	....
Quantum	$h\nu$	$\frac{19.86 \times 10^{-17}}{\lambda}$
Einstein	$Nh\nu$	$\frac{11.96 \times 10^6}{\lambda}$

DISTRIBUTION ABOUT SOURCE

In dealing with lamps the amount of energy radiated in various directions about the lamp may be significant. The distribution of energy about the lamp is rarely symmetrical. For instance, long tubular lamps such as fluorescent lamps obviously radiate very little energy in the direction of the axis of the lamp, and most of it is radiated at right angles to the axis. Often reflectors or other devices are used to give marked directional effects. Accordingly, the radiation in a given direction may be more significant than the total output of a lamp. For this reason, the energy is sometimes expressed in terms of the amount radiated per unit solid angle. A unit solid angle or steradian is the angle subtended at the center of a sphere by a portion of the surface equal to the square of the radius. The energy radiated per steradian in a given direction would be the energy which would fall upon an area equal to the square of the radius of an imaginary sphere with the lamp as the center. This is illustrated in Fig. 3. Since the area of a sphere is $4\pi R^2$ there are 4π steradians per sphere.

The intensity of radiation varies inversely as the square of the distance from the source, provided that the distance is large compared with the dimensions of the source and the intervening medium does not absorb the radiation. In dealing with long tubular sources (such as fluorescent lamps) the intensity at distances of less than the length of the lamp from the center of the lamp varies approximately as the first power of the distance.

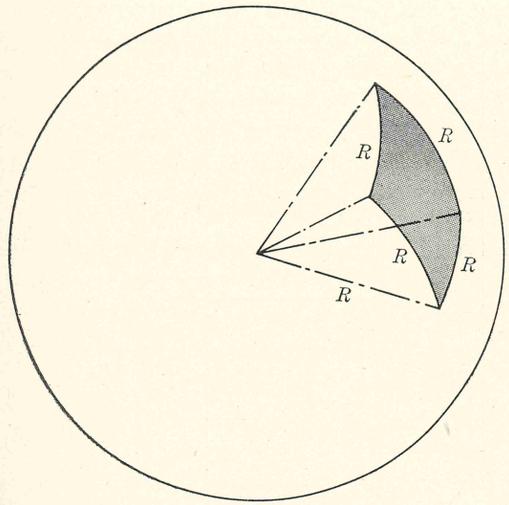

FIG. 3. The steradian.

KINDS OF SPECTRA

It is common practice to speak of the ultraviolet spectrum of a source even when no spectrum is formed. The various components present are described as if the radiation were passed through a spectroscope and spread out into a spectrum for examination. Obviously, the components are present whether the spectrum is actually formed or not.

One of the significant characteristics of any spectrum is its energy distribution. This is the amount of energy present at each of the wavelengths of the spectrum. This is rarely uniform but varies in a manner which is determined by many conditions. Spectra fall into three main classifications, continuous, line, and band spectra. Photographs of these three types are shown in Figs. 4*a*, 5*a*, and 6, respectively.

Continuous spectra are produced by incandescent bodies. They consist of continuous bands of radiation with energy present at all wavelengths. The energy may vary with wavelength throughout the spectrum in any manner. Figure 4*a* shows the continuous spectrum of an incandescent lamp. Figure 4*b* shows the relation between wavelength and energy in this spectrum.

Line spectra are produced by discharges in monatomic gases or vapors. They consist of bright lines concentrated at definite wavelengths separated by intervals in which no energy appears. Figure 5*a* shows a photograph of the line spectrum produced by a mercury arc.

FIG. 4. *a*. A continuous spectrum produced by an incandescent lamp. (Courtesy of Dr. F. J. Studer.) *b*. Energy distribution in the spectrum of an incandescent lamp. Shaded portion represents part of spectrum shown in Fig. 4*a*.

FIG. 5. *a*. A line spectrum produced by a glow discharge in mercury. (Courtesy of Dr. F. J. Studer.) *b*. Energy distribution in the spectrum of a glow discharge in mercury.

FIG. 6. A band spectrum produced by a glow discharge in nitrogen. (Courtesy of Dr. F. J. Studer.)

The energy distribution in this line spectrum of mercury is shown in Fig. 5*b*. The abscissae indicate the wavelength at which the lines occur, and the ordinates are proportional to the energy radiated in the various lines. The energy is distributed among these lines in accordance with principles which will be more fully discussed in Chapter 2.

Band spectra are produced by discharges in polyatomic gases or vapors. When examined under low dispersion they appear superficially

FIG. 7. Energy distribution in the emission spectrum of fluorescent zinc silicate.

to be a series of continuous bands with sharp edges at the long-wavelength side and shading off towards the short-wavelength side. Closer examination, however, shows that they are regular series of lines so closely spaced as to give the appearance of bands. Figure 6 shows a photograph of the band spectrum produced by a discharge in nitrogen.

A somewhat intermediate type of spectrum is produced by the phenomenon known as luminescence. This is the result of the excitation of certain substances by ultraviolet, X-rays, cathode rays, or chemical action. The resulting fluorescent or phosphorescent spectrum is one in which there are broad continuous bands over limited regions of the spectrum. This is the type of spectrum produced by fluorescent lamps, radioactive paints, cathode-ray and television tubes, and luminous bacteria. Figure 7 shows the energy distribution in the fluorescent spectrum of zinc silicate.

It is also possible to have combinations of these various types of spectra. In arcs a line or band spectrum due to the gas is often superimposed on the continuous spectrum of the incandescent electrodes. In fluorescent lamps the line spectrum of a gas is superimposed on the luminescent spectrum of the fluorescent coating.

Biological Units

Since ultraviolet produces marked physiological and therapeutic effects, it is sometimes convenient to evaluate it in terms of the effect which it produces rather than in terms of the energy involved. Thus it might be evaluated in terms of the amount required to cure rickets, to produce sunburn, to kill bacteria, or to produce other physiological effects.

Erythemal Unit

One of the pronounced effects produced by ultraviolet is erythema or reddening of the skin, which is discussed in greater detail in Chapter 7. The cause of this reaction is not yet thoroughly understood nor is the relation between erythema and other physiological effects, such as tanning or the cure of rickets. However, the amount of radiation which is required to produce erythema provides a convenient measure as well as an obvious limitation for ultraviolet dosage.

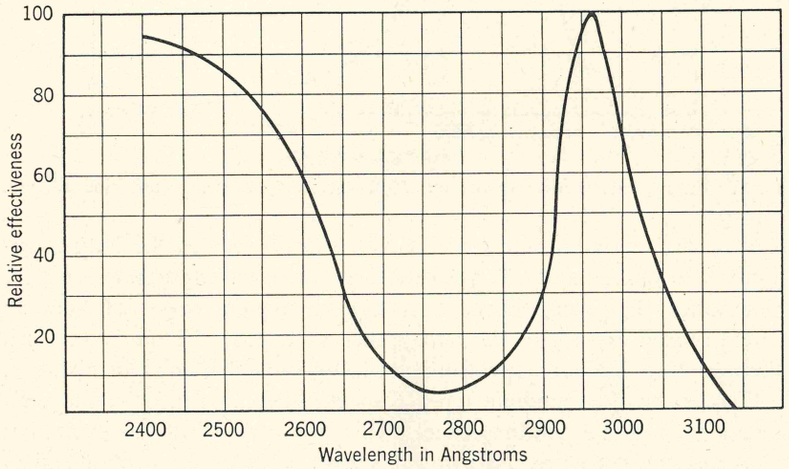

Fig. 8. The erythema curve showing the relative effectiveness of equal amounts of energy in different parts of the spectrum in producing erythema. (M. Luckiesh, L. L. Holladay and A. H. Taylor, *Trans. Illum. Eng. Soc.*, **26**, 703, 1931.)

Accordingly, it is convenient to use the ability of ultraviolet radiation to produce erythema as a unit of measure. The actual amount of energy required to produce erythema will vary with the wavelength of the radiation, since some parts of the spectrum are much more effective than others. Figure 8 shows the relative effectiveness of equal amounts of

energy in different regions of the spectrum in producing erythema. This is measured in terms of the effect produced by 2970 A radiation which is taken as the standard. From the curve it can be seen that 2970 A is the most effective wavelength and that the effectiveness of the radiation in producing erythema falls off very sharply with increase in wavelength to practically 0 at 3200 A. In the direction of shorter wavelengths the curve also falls off rapidly, passes through a minimum at 2800 A, and rises to a second maximum at about 2500 A. (This curve is discussed more fully in Chapter 7.) The reciprocals of the ordinates give the relative amounts of energy at the various wavelengths which would produce the same erythemal effect as a given amount of energy at 2970 A.

The erythema unit cannot, of course, be determined with the same accuracy as physical units, since there are great variations from one individual to another, as well as variations between different parts of the body. There are also appreciable variations in a given individual from time to time, depending upon factors such as physical condition and previous exposure. It is common knowledge that some people "burn" much more readily than others, and also that after being tanned the skin is much more tolerant of subsequent exposure. Furthermore, the skin when moist is much more susceptible to erythema than when dry. The method of evaluating erythema introduces still another variable. There is a latent period after exposure before reddening of the skin sets in. Accordingly, the length of time after exposure that the observation is made will affect the results. In spite of all these uncertainties the erythema unit based on the effect on the average untanned human skin provides a useful method of rating and comparing various sources of ultraviolet radiation.

The Council of Physical Therapy of the American Medical Association has adopted 10 μw of homogeneous radiation of wavelength 2967 A as the unit of erythemal flux or EU. The Illuminating Engineering Society and the International Commission on Illumination have standardized the term E-viton for this quantity of flux. Thus, 1 E-viton is the radiant flux which will produce the same erythemal effect as 10 μw of 2967 A radiation. For example, the wavelength 2600 A is only 60 per cent as efficient in producing erythema as is 2967 A. Accordingly, 16.6 μw at this wavelength would constitute an E-viton.

The E-viton, which is radiant energy weighted according to its ability to produce a certain (erythemal) effect, is quite analogous to the lumen which is used in photometry. The lumen is radiant energy weighted

according to its ability to produce visual brightness sensation. By means of this unit it is possible to compare the ability of various sources to produce erythema in terms of the effect produced by 10 μw of energy of wavelength 2967 A.

The total dose of ultraviolet is the product of E-vitons and time, say E-viton minutes, hours, or seconds.

One EU per cm^2 or 1 E-viton per cm^2 has been adopted as the unit of erythemal flux *intensity* and has been called the Finsen.

It requires about 25,000 μw-sec per cm^2 of wavelength 2967 A to produce a just perceptible erythema on the average untanned skin. This is equivalent to 2500 E-viton seconds per cm^2 or 2500 Finsen seconds.

The use of the erythema unit is possible only because of the validity of the reciprocity law. According to this law, the effect produced is proportional to the total amount of energy received, that is, to the product of the intensity of the radiation and the time of exposure. The same effect is produced by a short exposure to a very high intensity as by a longer exposure to a correspondingly lower intensity. This law does not hold for very low intensities.

Ordinarily we do not deal with monochromatic sources of radiation, so that the erythemal effectiveness depends upon the sum of the effectiveness of the wavelengths which are present. The total effect is calculated in the case of a line spectrum by adding the weighted intensities of the various lines of the source. The procedure is illustrated by the data in Fig. 9 and Table 4. Figure 9*a* shows the energy distribution in the spectrum of a typical quartz mercury arc. This spectrum consists of a number of sharp lines at definite wavelengths with intervals between them at which no energy is radiated. The abscissae show the positions of the lines; the ordinates are proportional to the energy radiated at each wavelength, that is, to the intensity of the lines. The effectiveness of this spectrum in producing erythema is calculated by multiplying each of the values of energy by the ordinate of erythema curve (shown in Fig. 8) at the corresponding wavelength. This gives the relative effectiveness of each of the lines in producing erythema or the equivalent intensity of 2967 A radiation which would produce the same erythemal effect as each of these lines. These values are shown in Fig. 9*b*. The sum of these values gives the equivalent energy of wavelength 2967 A which would have the same erythemal effect as the entire spectrum of this lamp. The energy values for the various lines, the corresponding values of the erythema curve, the products, and the resulting sum are given in Table 4. From Fig. 9*b* or the fourth column of the table it can be seen that most of the erythemal effect of this lamp is due to the

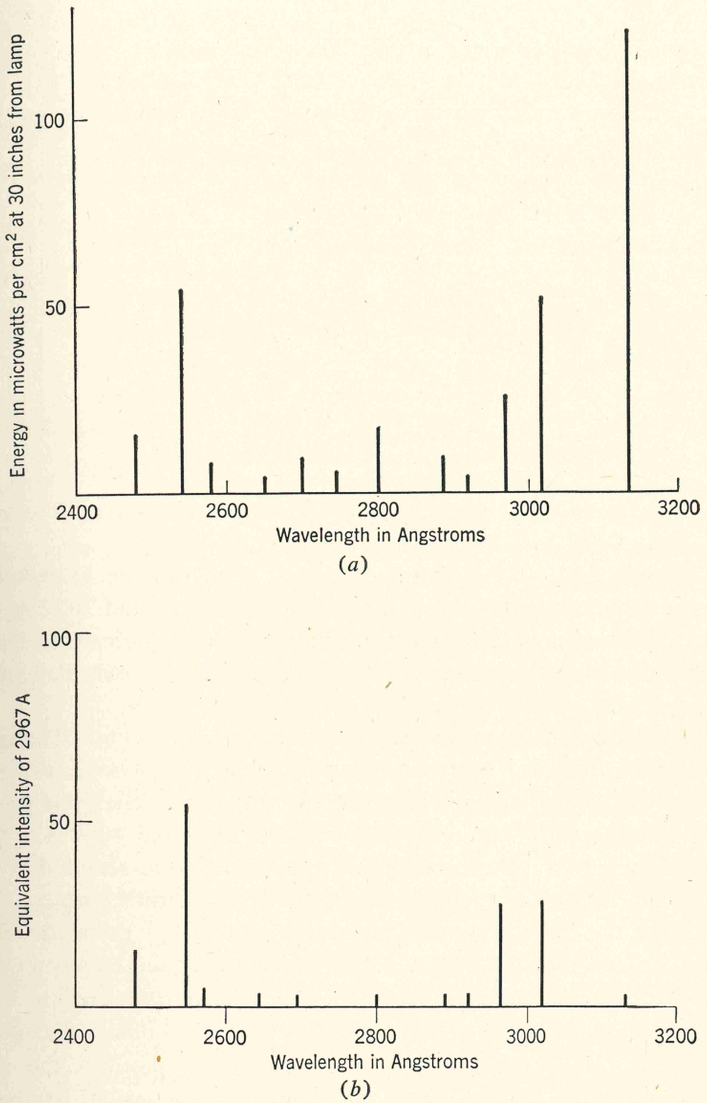

FIG. 9. *a*. Energy distribution in the various lines of the spectrum of a quartz mercury arc. *b*. Relative effectiveness of the lines of the quartz mercury arc shown in Fig. 9*a* in producing erythema.

TABLE 4

ERYTHEMAL EFFECTIVENESS OF QUARTZ MERCURY ARC

Wavelength	Intensity, $\mu w/cm^2$	Erythemal Effectiveness	Equivalent Intensity of 2967 A, $\mu w/cm^2$
2483	16.2	90	13.6
2537	55	80	44
2576	7	70	4.9
2652	4	30	1.2
2699	8	15	1.2
2753	6	5	0.3
2804	18.7	6	1.1
2894	9.8	25	2.5
2925	3.3	70	2.3
2967	27.0	100	27
3022	54	50	27
3129	122	2	2.4
	331.0		127.5

2537, 2967, and 3022 A lines. The very strong line at 3129 A contributes very little to the effect. The 2537 A, 2967 A, and 3022 A lines contribute more than three-quarters of the erythemal effect, although, as can be seen from the second column, they account for only half of the total energy.

The procedure is quite similar for a continuous spectrum. The ultraviolet part of the solar spectrum observed in Tucson, Arizona, as shown in Fig. 10 is a good example. In this spectrum, some energy is present at all wavelengths in the ultraviolet between 2900 and 4000 A. Each point of the curve indicates the energy in a 10 A band centered at that wavelength falling on a square centimeter of the earth's surface. The area under the curve is proportional to the total energy radiated. If we divide the spectrum into 10 A bands and multiply the energy in each band by the corresponding value of the relative effectiveness curve (shown in Fig. 8) and then add these values, we shall obtain the equivalent energy of wavelength 2967 A which would produce the same erythemal effect. Table 5 shows the intensity in the various bands, the corresponding values of erythemal effectiveness, and the equivalent energy at wavelength 2967 A which would have the same erythemal effect. The second and fourth columns show that the region between 2920 and 3020 A, although accounting for only about 43 per cent of

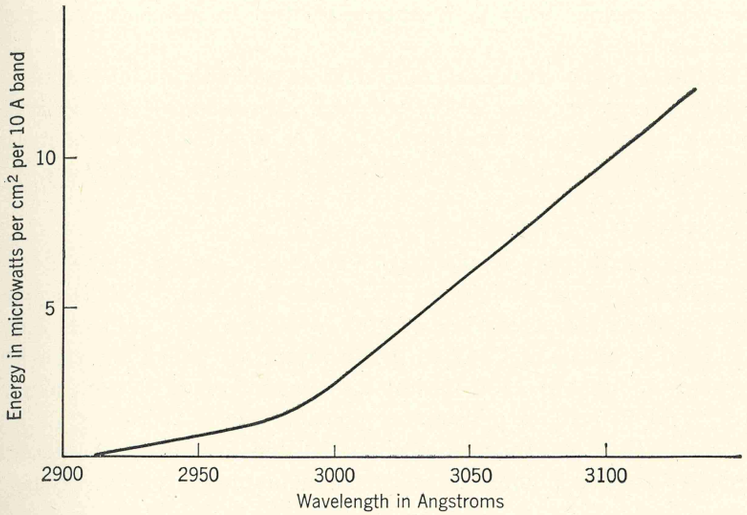

FIG. 10. Energy distribution in the solar spectrum at Tucson, Arizona.

TABLE 5

ERYTHEMAL EFFECTIVENESS OF SOLAR RADIATION *

Wave-length	Intensity, $\mu w/cm^2$ for 10 A Band	Erythemal Effectiveness, Per Cent	Equivalent, $\mu w/cm^2$ of 2967 A
2920	0.3	55	0.165
2930	0.4	60	0.24
2940	0.6	65	0.39
2950	0.8	70	0.56
2960	1.0	95	0.95
2970	1.1	100	1.10
2980	1.6	95	1.52
2990	2.0	90	1.80
3000	2.9	85	2.47
3010	3.6	80	2.88
3020	4.5	65	2.93
3030	5.4	30	1.62
3040	6.0	20	1.20
3050	7.1	10	0.71
3060	7.8	7	0.54
	44.1		19.56

* Calculated from E. Pettit, *Astrophys. J.*, **75**, 185 (1932).

the energy below 3060 A, is responsible for 79 per cent of the erythemal effect.

In this way the erythemal equivalent of any spectral distribution of radiant energy may be calculated and expressed as the equivalent amount of energy of wavelength 2967 A which would produce the same erythemal effect as the heterogenous radiation in question.

Miscellaneous Equivalents

Measurements have shown that 250,000 ergs per cm^2 at 2970 A are required to produce a minimum perceptible erythema. This is equal to 0.025 watt second per cm^2 or 25,000 μw-sec per cm^2. Since 1 EU or 1 E-viton is 10 μw of 2967 A, the exposure for minimum perceptible erythema is equal to 2500 E-viton sec per cm^2 or 42 E-viton min per cm^2. The intensity of midsummer noonday sun is about 1.8 E-vitons per cm^2. Thus an exposure of about 20 min to midsummer noonday sunlight would be required to produce a minimum perceptible erythema.

Germicidal Units

Another of the important effects produced by ultraviolet radiation is its lethal effect on bacteria. This is particularly marked for the shorter wavelengths in the ultraviolet. In making use of the germicidal effect of ultraviolet it is convenient to use a unit which is a measure of this effect. W. F. Wells has suggested the unit of kill for bacteria suspended in air as the removal or death of standard test organisms equivalent to that produced by one air change. This is equivalent to the killing of 63.2 per cent of the organisms present. This unit of kill is called the Lethe.[4] The ultraviolet exposure (product of intensity and time) required to produce this kill is a unit lethal exposure. The energy equivalent to unit lethal exposure depends upon the nature of the organism under consideration and on the wavelength of the radiation. For *B. coli* under conditions of 100 per cent humidity a lethal exposure corresponds to 0.01 watt-min per ft^2 of radiation of wavelength 2537 A or approximately 10 μw-min per cm^2.

The American Medical Association [5] has tentatively adopted as a unit of germicidal intensity or GU 100 μw per cm^2 of radiation of wavelength 2537 A.

At other wavelengths the energy must be weighted according to the germicidal effectiveness curve which will be discussed in Chapter 7.

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2 Arcs

Introduction

The most efficient and useful sources of ultraviolet are the arcs which occur when a current of electricity is passed between electrodes separated by a gas or vapor. The passage of current through the gas results in various phenomena, one of which is the emission of radiation. The amount of this radiation which lies in the ultraviolet varies with the nature of the arc. Arcs fall into two main classes, open and enclosed.

Open arcs, of which the carbon arc is a typical example, are discharges taking place between electrodes exposed to the atmosphere.

Enclosed arcs, of which mercury vapor sunlamps are typical examples, are discharges through a gas or vapor contained in an envelope, usually of quartz or glass. Hence, they may take place through any desired gas or vapor and at pressures ranging from a few microns up to hundreds of atmospheres. The pressure is limited only by the strength of the envelope. The gases and vapors used include such diverse substances as hydrogen, helium, argon, neon, krypton, xenon, mercury, cadmium, zinc, tellurium, and magnesium.

The electrodes used in arcs also show wide variation. They may be of the hot- or cold-cathode type or they may consist of pools of the metal in the vapor of which the discharge takes place.

In general, arcs operate at high current and low voltage, that is, currents of the order of amperes and voltage drops of less than 100 volts.

The spectrum of most arcs is chiefly due to the discharge through the gas or vapor and so is usually of the line or band type. In high-pressure arcs there is also a continuous background over a part of the spectrum. In some cases, such as the carbon arcs, the incandescent electrodes may also contribute a continuous component to the spectrum so that line and continuous spectra may be present in various proportions.

The development of the open arc began with its invention by Sir

Humphry Davy sometime between the years 1802 and 1808. Davy operated an arc between charcoal electrodes in air. He is also responsible for the name "arc" because of the bow shape of the discharge occurring between horizontal electrodes. The invention of the arc could not have taken place any earlier because a suitable source of high voltage was not available until Volta announced his pile in 1800.

The development of the enclosed mercury arc began with the observation by Wheatstone [1] that a brilliant light is emitted when mercury is vaporized in the electric arc. He described its characteristics before the British Association in 1835. In 1852 E. H. Jackson of Soho patented a mercury lamp consisting of two carbon electrodes, the lower one of which had a recess to contain a small amount of mercury. A year later Christopher Binks produced and patented a lamp having two mercury electrodes in a glass case. He also provided means for condensing the vaporized mercury.

Although mercury took part in these discharges, the first true vapor lamp was not constructed until 1896 when Dowsing and Keating passed a discharge through mercury in a partly evacuated tube. These early arcs went out after operating for a time because of the increase in pressure of the vapor. Cooper Hewitt devised a lamp in which the mercury was condensed and returned to the cathode pool at the same rate at which it was vaporized and so avoided this difficulty. This initiated the successful commercial development of mercury lamps. The development of fused quartz and ultraviolet-transmitting glass have been large factors in making arcs of use for the generation of ultraviolet.

In spite of the tremendous range in their nature, arcs have certain features in common which will be considered before passing to a discussion of the individual types.

Definition

The passage of electricity through a gas or vapor results in a number of closely related phenomena such as brush discharges, corona, sparks, glow discharges, and arcs. Each of these has fairly well-defined characteristics, but the dividing line between one type of discharge and another is not always easy to determine. Compton [2] has defined an arc in terms of two distinctive properties, the volt ampere characteristic and the cathode drop. According to Compton's definition an arc is "a discharge of electricity between electrodes in a gas or vapor, which has a negative or practically zero volt ampere characteristic and a voltage drop at the cathode of the order of the minimum ionizing or exciting potential

of the gas or vapor." * These two properties will be considered in the following sections.

Volt Ampere Characteristic

The relationship between the current and voltage for an ohmic resistance, called its volt ampere characteristic, is shown in Fig. 1*a*. This is a positive volt ampere characteristic, that is, the voltage increases with increase in current.

Figure 1*b* shows a typical volt ampere characteristic of an arc. The voltage decreases with increase in current; hence the arc is said to have

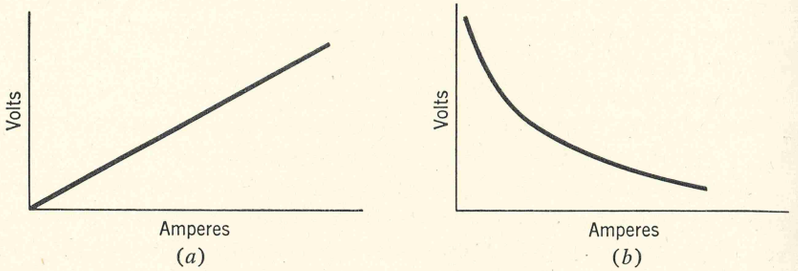


Fig. 1. Volt ampere characteristics. *a*. Relation between current and voltage for an ohmic resistance. *b*. Relation between current and voltage for an arc.

a negative volt ampere characteristic. Empirical equations have been developed which fit many arc characteristics. The one developed by Mrs. H. Ayrton is of the form

$$V = a + bl + \frac{c + dl}{i}$$

where a, b, c, d are constants depending upon the nature of the gas and the electrodes, l is the length of the arc, and i is the arc current.

Nottingham [3] developed an equation for atmospheric arcs of constant length of the form

$$V = A + B/I^x$$

where A and B are constants and x depends on the anode material. The values of x for carbon, tungsten, and copper are 1, 1.38, and 0.67, respectively.

* Under some conditions, arcs may have positive volt ampere characteristics. The negative type, however, is more common among the arcs used for the production of ultraviolet.

Any device with a characteristic such as this is inherently unstable. This is illustrated in Fig. 2. Suppose the arc to be operating on a fixed supply voltage V_1 corresponding to a current I_1 through the arc. A slight transient increase in the arc current to I_2 would result in a drop in the voltage required by the arc to V_2. This would leave an excess of voltage, $V_1 - V_2$, available which would increase the current still further with a consequent further drop in the voltage requirement of the arc. This

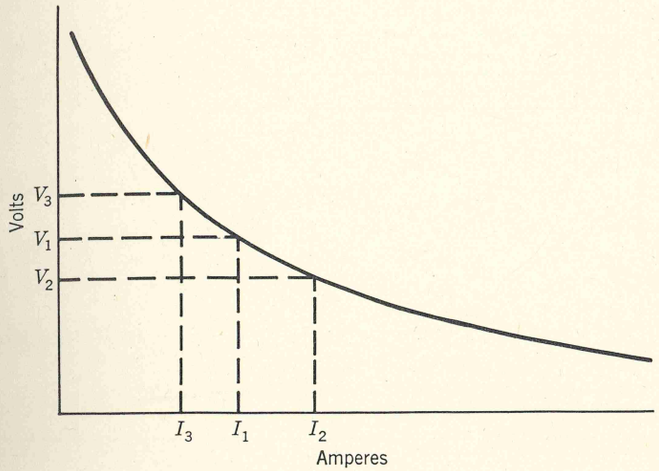


Fig. 2. Instability of an arc.

unstable condition would lead to a runaway in which the arc current would increase without limit until the arc or some part of the circuit was destroyed by excessive current.

Similarly, a transient decrease in arc current from I_1 to I_3 would result in an increase in the required voltage to V_3. Since this is more than V_1, the available voltage supply, the current would decrease still further and the arc would eventually go out.

The inherent instability of arcs is overcome in practice by operating them in series with a resistance (or reactance in the case of a-c arcs). This is called a ballast resistance or reactance. The heavy curves *a* and *b* of Fig. 3 show the volt ampere characteristics of an arc and an ohmic resistance, respectively. The dashed curve *c* shows the volt ampere characteristics of the series combination of these two obtained by adding the voltage ordinates for the corresponding values of current. The characteristic of the combination has a positive slope. Accordingly, the arc

will be stable for values of current and voltage along curve *c*. If the arc is operating at a current I_1 corresponding to a supply voltage V_1, a slight transient increase in current to I_2 would require voltage in excess of the supply and the current would drop back towards I_1. A decrease in current to I_3 would result in the supply voltage being in excess of the arc requirements which would bring the current back towards I_1 again.

Another way of representing these facts is shown in Fig. 4. The

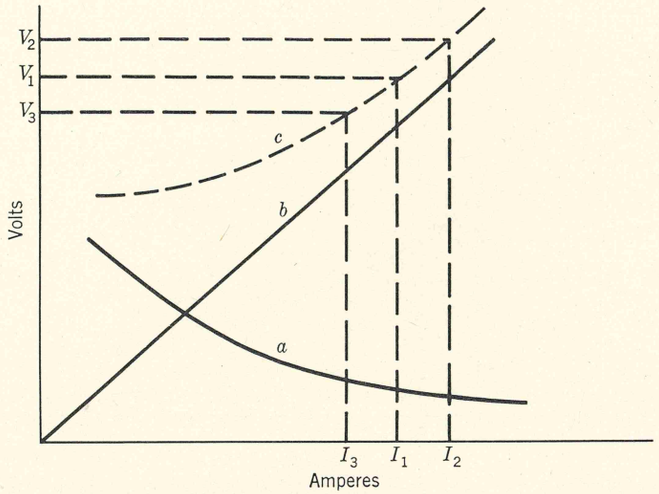


FIG. 3. Stability of an arc with a ballast resistance. *a*. Arc characteristic. *b*. Ballast characteristic. *c*. Combined characteristic.

heavy curve *A* represents the volt ampere characteristic of the arc. The straight line *B* is a plot of $E - IR$, the supply voltage minus the *IR* drop across the ballast resistance, as a function of arc current. This voltage in excess of the *IR* drop in the resistance represents the voltage available for the operation of the arc. The two lines intersect at the points *x* and *y* at which the voltage is sufficient to maintain the arc. However, inspection shows that the point *x* corresponds to a condition of unstable equilibrium, so that the arc current will increase until it finally stabilizes at point *y*. At this point a transient increase in current to I_1 will result in a decrease in the voltage available for operation of the arc to V_1. This is less than the requirement of the arc which would bring the arc back towards *y*. Similarly, a decrease in the arc current to I_2 would result in an increase in the voltage available for the arc to V_2. This is in excess of the requirement of the arc which would also tend to bring

the arc back to the operating point *y*. The line *C* corresponds to a higher value of resistance. In this case the value chosen is so high that the line does not cut the arc characteristic, and so the conditions for operation are not satisfied. The highest possible operating resistance is indicated by the line *D* which is tangent to the arc characteristic.[4]

This discussion is an oversimplification of the problem, as it considers

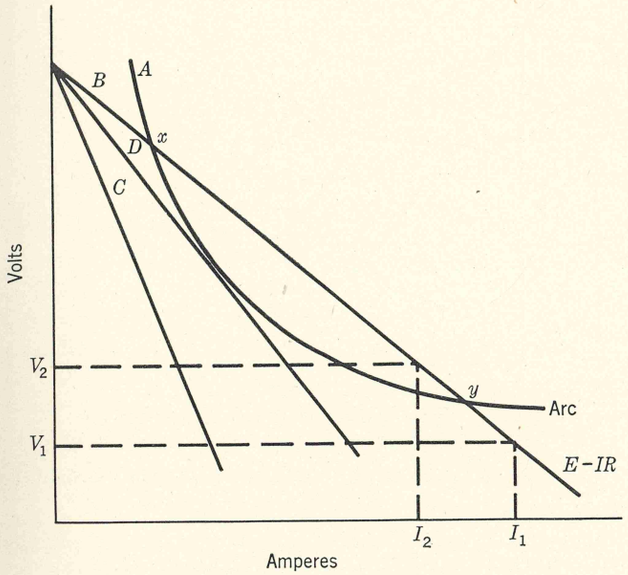


FIG. 4. Conditions for stability of an arc. (P. Copeland and W. H. Sparing, *J. Applied Phys.*, **16**, 302, 1945.)

only the dynamic arc characteristic. In the case of an arc, say in mercury vapor, any change in arc current or voltage results in a change in temperature which in turn alters the vapor pressure and so results in a further change in the properties of the arc. Accordingly, it can be seen that the changes in arc characteristics depend upon the speed with which the changes take place. After any alteration in current or voltage operating conditions, an appreciable period must elapse before temperature equilibrium is established and the arc again stabilized. Dynamic characteristics measured under conditions in which the current is changed so rapidly that the pressure does not have time to change are very different from static characteristics in which the pressure is allowed to reach a new equilibrium with each change in current. This is shown

in Fig. 5 where the heavy curves represent dynamic characteristics taken at temperatures T_1, T_2, and T_3, corresponding to pressures P_1, P_2, and P_3. Along each of these curves the voltage and current are varied so rapidly that time is not allowed for a new temperature equilibrium to be established. The dotted curve represents the static characteristic where time has been allowed for the pressure to come to new equilibrium value at each point. This should not be confused with the positive volt ampere curve since it does not represent constant-pressure conditions.

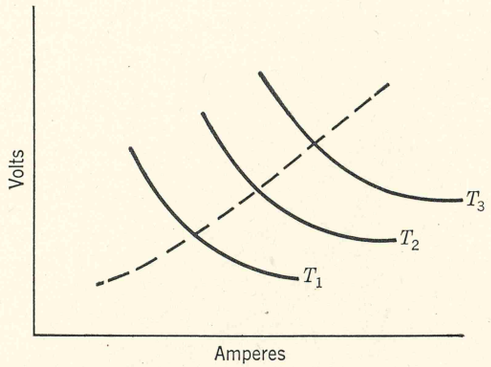


FIG. 5. Static and dynamic arc characteristics.

POTENTIAL DISTRIBUTION IN THE ARC

The potential distribution between the electrodes of an arc is one of its most characteristic features. The potential does not rise uniformly from cathode to anode. Just outside the cathode, it rises sharply. This is followed by a somewhat smaller rise, after which it rises at a uniform rate per unit length of arc almost to the anode. At the anode there may be either a small, more rapid rise or a small drop, depending upon conditions. The potential distribution in a glow discharge is shown schematically in Fig. 6. The horizontal scale in the vicinity of the cathode is greatly exaggerated, as the initial drop takes place in a distance of the order of a few electron mean free paths, approximately 10^{-2} cm. This initial drop in potential near the cathode is known as the cathode fall, and it is usually of the order of 10 to 20 volts. The potential distribution is related to visible regions in the discharge which are indicated in the lower part of the figure.

Although arcs are used for the production of radiation, the radiation

is only a by-product of the processes which make the gas conducting. The fundamental process in the arc is the passage of current. This is made possible by the emission of electrons from the cathode and the production of positive ions in the space between the electrodes. All the other phenomena in the arc are subordinate to these.

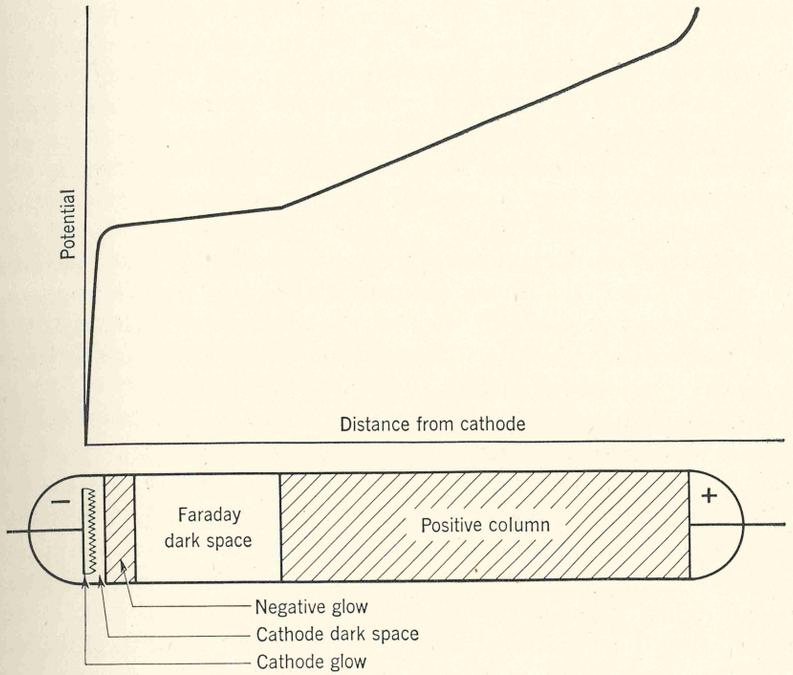


FIG. 6. Potential distribution in a glow discharge.

The current in the arc is carried mainly by electrons released at the cathode. The electron emission is the result of several processes. These include several phenomena by which the gas gives up energy to the cathode and so raises its temperature sufficiently to yield the required current by thermionic emission. In a-c arcs the heating of the cathode by electrons during the positive half cycle is also an important factor. The other process which is not clearly understood is a field effect whereby the field due to a high concentration of positive ions near the cathode is sufficient to pull the required number of electrons from the cathode.

In the cathode fall the electrons are accelerated and produce the posi-

tive ions which in turn maintain the emission from the cathode. The electrons give up most of their energy in forming positive ions close to the cathode and drift through the remainder of the space to the anode at greatly reduced velocities. Once past the region of the cathode fall, the electrons produce only sufficient ions to maintain the conductivity of the gas. This region in which the numbers of ions and electrons are equal is called a plasma.

The region between the cathode fall and the anode is one of uniform luminosity known as the positive column. From the utilitarian point of view, the positive column is the important part of most arc discharges, since, in this region of small voltage drop per unit length and low power consumption, large numbers of atoms are excited to emit radiation. In point of fact, it is not an essential part of the discharge but may be thought of as merely filling up the region between the cathode fall and the anode and providing a conducting path by which the electrons may reach the anode. If a tube is constructed with moveable electrodes, as the electrodes are separated, the cathode fall remains unchanged, but the positive column increases in length and the voltage across the tube increases with increasing length of the positive column.

In glow discharges at low pressures, the cathode fall region is seen to have a visible structure consisting of luminous and dark regions which going outward from the cathode are known as the Aston dark space, the cathode glow, the cathode dark space, the negative glow, and the Faraday dark space. Probe measurements show that the cathode fall is not uniform over this entire region but can be correlated with this structure. These regions are shown in Fig. 6, except for the Aston dark space, which is not usually visible. In high-pressure arcs, these critical regions merge and the discharge appears to consist essentially of a positive column.

Arc Temperature

The temperature of arcs varies over a wide range. The temperature of the gas in the discharge may be considerably higher than that of the electrodes. In speaking of the temperature of the gas, a distinction is made between the temperature of the atoms and molecules and the temperature of the free electrons. The temperature is defined in terms of the mean kinetic energy of the molecules or electrons as the case may be. In low-pressure arcs, these two are not the same. The temperature of the gas molecules may be a few hundred degrees or less, as in fluorescent lamps, whereas the electron temperature may be as high as 40,000°K.

This results from the processes by which the electrons acquire energy from the electrostatic field and communicate it to the gas by collision.

At each collision, the electron loses a fraction of its energy $2m/M$ (where m = mass of electron and M = mass of gas molecule). Because of the disparity in the masses of electrons and gas molecules this fraction is very small, 0.00004 in the case of nitrogen. In the steady state the electron loses (on the average) as much energy in each collision as it has gained since the last previous collision. At low pressures and high fields, since much energy is gained between collisions, the total energy of the electron must become very large in order that this small fraction may equal the amount gained between collisions. On the other hand, at higher pressures where the mean free path becomes small the electron gains little energy between collisions and the total energy need not be so large in order to satisfy this condition. Thus at low pressures the electron energy is large compared with the gas energy and the electron temperature is high compared with the gas temperature. As the pressure is increased, however, the electrons and gas molecules approach thermal equilibrium. This equilibrium takes place at pressures of the order of 10 mm of mercury; hence this marks the transition between high- and low-pressure arcs.

The temperature of the arc stream of a high-pressure mercury arc may exceed 6000°K. The temperature of the positive column of a few other atmospheric pressure arcs is as follows: [5]

Cored projection carbon	5500°K
9.5 mm tungsten	6440°K
Tungsten welding arc	6150°K
Coated iron welding arc	6020°K

Hot Cathodes

The construction of the anode has relatively little effect on the characteristics of low-pressure arcs. Refractory materials such as tungsten, molybdenum, tantalum, and carbon are most commonly used.

The construction of the cathode, however, profoundly influences the behavior of the arc. This is because the cathode must supply the electrons which carry most of the arc current. The efficiency with which electrons are liberated at the cathode in turn determines the positive-ion current required and so to a considerable extent affects the characteristics of the discharge. By making the cathode of material which is a good emitter of electrons and heating it independently of the arc current, it is possible to reduce the cathode drop. This reduces the voltage required to maintain the arc. It also makes the operation of the arc more

reliable and reproducible and facilitates starting. Cathodes which are heated by a source of powder independent of the arc are said to be separately excited. Cathodes heated by the arc current are said to be self-excited.

The relationship between thermionic emission and temperature is given by Dushman's equation

$$I = AT^2e^{-b/T} \text{ amp/cm}^2$$

where I is the thermionic emission in amperes per square centimeter.
T is the absolute temperature.
A and b are constants depending upon the nature of the material.

Thus, for any given material the higher the temperature the larger is the emission. However, in practice the temperature is limited by the fact that the higher the temperature the greater is the evaporation from the surface and consequently the shorter is the life of the cathode. Table 1

TABLE 1

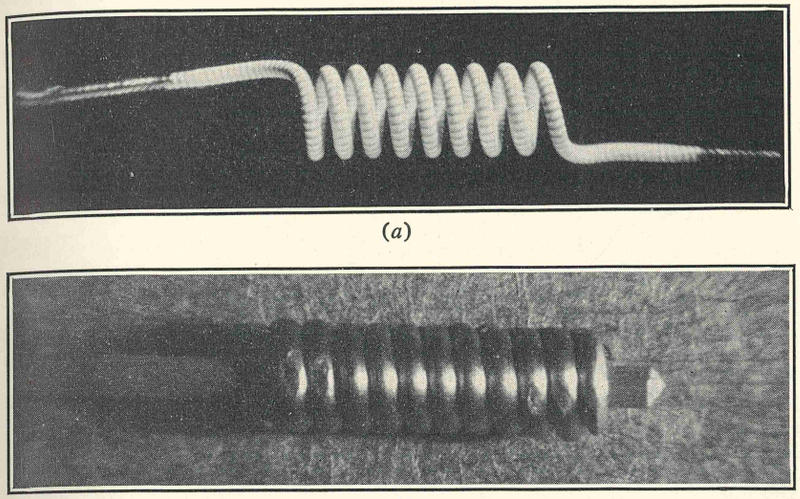
PROPERTIES OF SOME COMMON CATHODE MATERIALS

Material	A *	b *	Normal Operating Temperature, °K	Emission per sq cm, amps	Efficiency of Emission, ma/W
Tungsten	60.2	52,400	2400	0.10	1.8
Molybdenum	60.2	50,900	2000	0.0023	0.12
Tantalum	55	48,600	2000	0.003	0.14
Thoriated tungsten	15.5	33,200	2000	1.61	68.0
Oxide-coated cathode	....	.....	1000	1.0	100

* S. Dushman, *Encyclopaedia Britannica*, **22,** 75 (1947).

gives some of the properties of the more commonly used cathode materials. Column 1 gives the material, columns 2 and 3 give the value of A and b, column 4 gives reasonable operating temperatures, and columns 5 and 6 give the emission per square centimeter and the emission per watt input to the cathode at these temperatures. This last quantity is a very significant one from the practical point of view, since it represents the efficiency of the cathode. A high efficiency is desirable in order to cut down the energy input to the arc. As is shown in column 6, oxide-coated cathodes are the most efficient and are used in most enclosed arcs.

Cathodes are constructed in various ways, depending upon the requirements to be met. The simplest form is, of course, a U-shaped filament. This is suitable, however, only where the electron current required is small. For a large current a large filament area is required. This can be obtained by increasing the diameter or the length of the filament. The former would require excessive filament heating currents and the latter, excessive filament volts. Also a high voltage applied



(*a*)

(*b*)

FIG. 7. Various forms of thermionic cathodes. *a*. Overwound oxide-coated cathode. *b*. Thorium-insert cathode. (Courtesy of General Electric Co.)

between the filament leads would result in an arc forming across them which would short-circuit and possibly burn out the filament.

Accordingly, a number of different expedients are used in order to gain increased area. One of these is shown in Fig. 7*a*. This shows an overwound cathode. This is a tungsten filament overwound with a helix of tungsten or nickel. The surface is then covered with the usual coating mixture of barium oxide and strontium oxide. This is the type of cathode used in fluorescent lamps.

A somewhat different type of cathode used in high-pressure lamps is shown in Fig. 7*b*. In this case the overwinding is a heavy tungsten coil. A small piece of thorium metal inserted between this and the lead melts and activates the surface during the processing of the lamp.

Numerous other types of cathodes are used in arcs but are not of great importance in lamps.

In some arcs, the cathodes are heated by a source of voltage independent of the main arc supply. Such a circuit is indicated schematically in Fig. 8. Other examples are given in greater detail in the discussion of individual types of arcs.

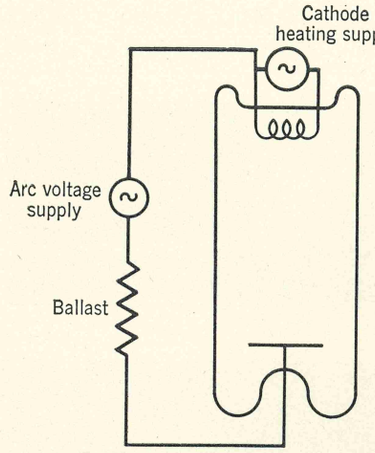


FIG. 8. Arc with separately excited cathode.

The advantages of hot cathodes are increased stability in operation, low arc voltage drop, and operation on either alternating current or direct current.

PRODUCTION OF RADIATION

The radiation is actually a by-product of the passage of current in an arc, although from a practical point of view of extreme importance. It is in this important by-product that the arcs show their greatest diversity.

The spectra of arcs depend on the nature of the gas molecules through which the discharge takes place. The molecules can exist in a number of discrete states. The passage of electrons through the gas results in exciting the molecules to various of these states. In making transitions from one state to another, the atoms emit radiation of definite wavelengths. The probability of these various transitions depends upon the nature of the gas, its pressure, and the electrical conditions in the discharge. Although it is possible to interpret these phenomena, they are too complex to permit the prediction of the energy distribution from fundamental considerations in anything but a qualitative manner in most cases.

GENERAL CHARACTERISTICS OF MERCURY ARCS

Mercury arcs have been widely used for the generation of ultraviolet. There are several reasons for the choice of mercury. Its spectrum is rich in lines in the ultraviolet. These are listed in Table 2. Mercury is fairly inert and does not react with electrode materials, nor does it attack glass appreciably. Its vapor pressure lies in a convenient range for lamps which operate near room temperature.

TABLE 2

LINES IN THE ULTRAVIOLET EMISSION SPECTRUM OF MERCURY

Angstroms	Angstroms	Angstroms
1269.7	2399.4	3125.6
1527	2482.7	3131.56
1592	2534.8	3131.84
1599	2536	3341.48
1650	2652	3650.15
1677.9	2698.9	3654.83
1783.3	2752.8	3662.87
1798.7	2803.5	3663.27
1849	2847.7	3906.4
1942	2893.6	3983.99
2224.7	2967.28	4046.56
2378.3	3021.50	

A wide variety of mercury arcs is available commercially. They differ from each other in such respects as pressure, bulb shape, material, reflector, electrodes, starting mechanism, and other features which suit them to perform specific tasks. Literally hundreds of different kinds have been developed. It is beyond the scope of this book to discuss all of them. Nor is any attempt made here to describe all the currently commercially available mercury arcs. Those chosen for discussion are typical of the more important varieties. Likewise, European arcs are not discussed. Many of them are described in Ellis and Wells, *Chemical Action of Ultraviolet.*

Essentially, they are characterized by the mercury vapor pressure. This parameter of pressure is the important one in determining the kind of radiation generated by the discharge. The radiation is then further modified by filters which may be external or may be incorporated in the lamp envelope.

All these lamps generate all the lines of the mercury spectrum, although not all the lines are necessarily transmitted by the bulb. The relative energy in the various lines, however, varies with the character of the discharge.

From a consideration of the fundamental nature of the discharge and of the envelope it should be possible for the reader to compare any given arc with one of the types discussed here and so obtain an approximate estimate of its spectral characteristics.

In the earliest form of lamp the electrodes consisted of a mercury pool at each end of the tube. The lead-in wires made contact with this. Later a metallic electrode, first of iron and then of tungsten, was substi-

tuted for the anode pool. In more recent forms an oxide-coated cathode has been substituted for the cathode pool. None of these changes affect the essential nature of the radiation.

Starting of Mercury Arcs

The voltage required to start an arc is usually considerably higher than that required to maintain it once it has been started. Several methods have been used for initiating the discharge in mercury lamps. Pool-type lamps are started by tipping the lamp so that the mercury short-circuits the electrodes. The voltage is then applied and the lamp raised to the operating position. As the mercury path is broken an arc starts across the gap and forms a cathode spot and is sustained after the lamp is in its normal position. Obviously, this method is suitable only for lamps containing a considerable quantity of mercury.

The cathode spot is a small, very bright area on the cathode pool from which the electrons are emitted. The process by which they are emitted is not clearly understood in the case of low-melting-point metals. The cathode spot moves about on the surface of the mercury in a random manner at a very high velocity (of the order of 10 m per sec). The current density of the cathode spot has been determined to be between 50,000 and 220,000 amp per cm^2.[6] A minimum current of about 3 amp is required to maintain the cathode spot.

Another common method of starting involves the use of an inductance or a high-reactance transformer in the circuit which supplies a momentary high-voltage "kick" to start the arc. Once the arc has struck, the drop in the reactance reduces the voltage to the value required for normal operation of the arc.

A third method involves an auxiliary electrode which is placed close to the cathode. A discharge starts between this electrode and the cathode but is limited to a very small current by a high resistance. However, the ions and electrons produced in this discharge drift into the path of the main arc so that it can jump readily to the main anode.

Lamps with mercury pool cathodes are of necessity essentially d-c devices. This is because the mercury cathode spot is extinguished when the voltage falls to zero at the end of each half cycle and is not reestablished at the lamp's operating voltage. In order to operate them on alternating current, they must be provided with two anodes and used in a rectifier circuit. Thus current is continually drawn from the cathode and alternates between the two anodes. The cathode spot is kept "alive" by inductance during the transition from one anode to the

other. The mercury pool also places limitations on the operation position of lamps employing it. Figure 9 shows an early form of d-c mercury pool-type lamp for horizontal and vertical operation. Figure 10 shows schematically a pool-type lamp for a-c operation and the appropriate circuit. The mercury pool obviously places limitations on the position of the lamp, the method of starting, and the use of alternating current. Pool-type lamps have been largely replaced by lamps with thermionic cathodes. These have the advantages of operating on alternating current, starting easily, and being steady in operation. The discussion of pool-type lamps is given chiefly because of their historical interest.

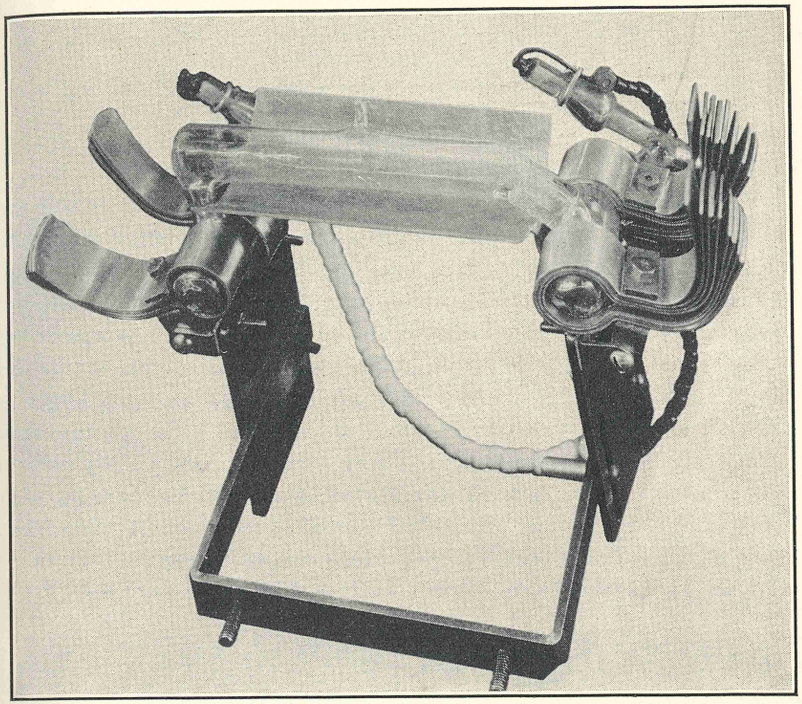


Fig. 9. Pool-type quartz mercury arc for vertical or horizontal operation. Now superseded. (Courtesy of Hanovia Chemical and Mfg. Co.)

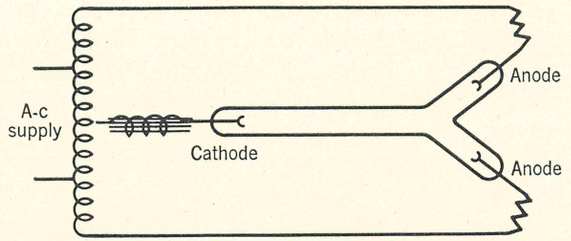


FIG. 10. A-c operated pool-type mercury arc.

VARIATION WITH TEMPERATURE AND TIME

When a mercury arc is first started, the arc current is high and the voltage low. As the arc operates the temperature and hence the vapor pressure rises. The current falls and the voltage increases. Eventually, the lamp reaches temperature equilibrium with its surroundings, and the heat loss by radiation, conduction, and convection becomes equal to the watts input. For constant output, careful control of the ventilation about a lamp is very important. The pressure of the mercury vapor is determined by the coolest spot on the bulb wall and is the pressure corresponding to this temperature. (These remarks apply equally well to other metal vapor arcs.) The variation of current and voltage with temperature and time is greatly influenced by the electrical characteristics of the ballast. Table 3 gives the pressure of mercury vapor at various temperatures.

LIMITED-PRESSURE-TYPE LAMPS

In many of the modern mercury lamps greatly increased stability and insensitivity to ambient temperature are obtained by limiting the amount of mercury in the lamp. Instead of an excess of liquid mercury in the bulb, the amount introduced is chosen so that it is completely vaporized at the normal operating temperature of the lamp. When all the mercury is vaporized, the lamp is relatively insensitive to changes in ambient temperature, since changes in pressure follow the gas laws instead of the temperature vapor pressure curve. For example, a change in temperature from 20 to 100°C will increase the pressure of mercury vapor in contact with the liquid from 0.012 mm to 0.273 mm, more than twentyfold, but the pressure of the unsaturated vapor will be increased by only 34 per cent.

TABLE 3

MERCURY VAPOR PRESSURE AT VARIOUS TEMPERATURES *

Temperature, Degrees C	Pressure in Millimeters
0	0.000185
10	0.000490
20	0.001201
30	0.002777
40	0.006079
50	0.01267
60	0.02524
70	0.04825
80	0.08880
90	0.1582
100	0.2729
150	2.807
200	17.287
300	246.80
400	1574.1

* *Handbook of Chemistry and Physics*, 1948.

MODERN UVIARC *

A typical a-c lamp with a thermionic cathode is shown in Fig. 11. The radiation from a lamp of this kind includes all the characteristic lines of mercury except the very short wavelengths which are absorbed by the quartz. It is a very efficient source of ultraviolet.

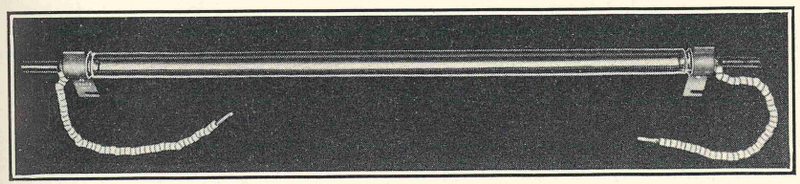


FIG. 11. A modern high-pressure a-c mercury arc. (Courtesy of Hanovia Chemical and Mfg. Co.)

Table 4 shows the energy distribution of the radiation from a lamp of this type. The second column shows the energy in the various lines expressed as per cent of the input to the arc tube. The third column shows it in watts. The fourth column shows the energy at each wavelength which falls on a square-centimeter area at a distance of 1 meter

* Uviarc is a General Electric trade name for a group of lamps which are high in ultraviolet output.

from the arc. About one-fifth of the total energy input to the arc tube is radiated in the ultraviolet. From the table it can be seen that the strongest ultraviolet lines are those at 2537 A, 2652 A, 3022 A, 3129 A, and 3650 A. The energy in these lines comprises 66 per cent of the ultraviolet from this discharge.

The lamp radiates about 80 watts of energy of wavelength shorter than 3130 A. The erythemal equivalent of this energy distribution,

TABLE 4

ENERGY DISTRIBUTION OF RADIATION FROM MERCURY VAPOR ARC IN QUARTZ *

Arc length	11.6 cms
Arc watts	560
Temperature	395°C

Wavelength in Angstroms	Energy Radiated in: Per Cent of Energy Input to Arc	Watts	Milliwatts/cm² at 1M from Arc
6234	0.3	1.7	0.017
5700	5.5	31	0.31
5460	3.9	22	0.22
4960 and 4358	3.6	20	0.20
4045 and 3906	3.0	17	0.17
3660	6.2	35	0.35
3341	0.7	3.9	0.039
3130	4.2	24	0.24
3025	2.2	12	0.12
2967	0.9	5.0	0.05
2925, 2893, and 2803	0.8	4.5	0.045
2752 and 2700	0.5	2.8	0.028
2652	1.5	8.4	0.084
2571	0.6	3.4	0.034
2537	1.6	9.0	0.090
2482, 2400, 2360, and 2300	1.5	8.4	0.084
1942 and 1849	0.4	2.2	0.022
Total ultraviolet less than 3800 A	21.1	118.6	1.19

* Calculated from *Hanovia Bulletin for Type A Lamp*, April, 1946.

that is, the amount of energy at 2967 A which would produce the same erythemal effect, is about 34 watts or 3,400,000 E-vitons.

Table 5 shows the energy distribution in broad spectral regions instead of line by line for an arc of similar type but of somewhat lower wattage input and smaller dimensions made by a different manufacturer. The same data are also shown graphically in Fig. 12. These data are not consistent with those in Table 4, owing to a difference in the arc

dimensions and input values. Arcs of different sizes made by different manufacturers will show considerable variation in output, but the essential nature of the spectrum remains the same, as can be seen by comparing Tables 4 and 5.

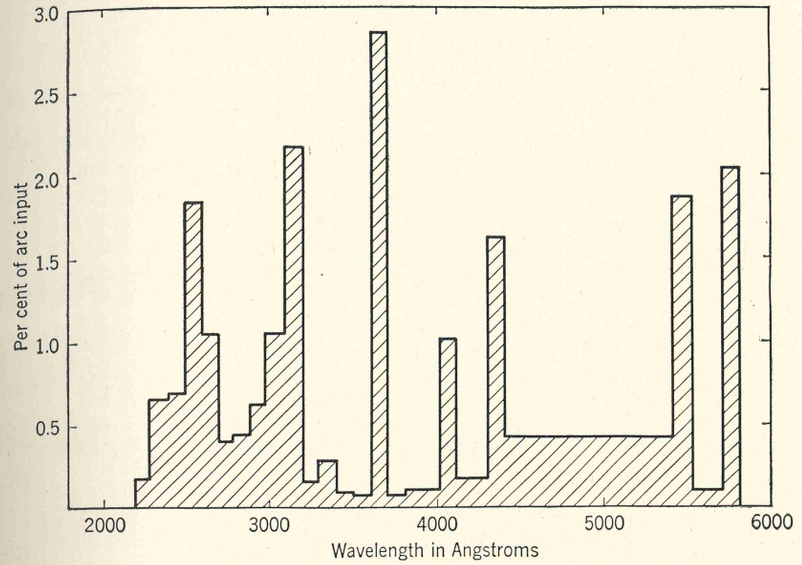


FIG. 12. Energy distribution in spectrum of UA-2 mercury vapor arc in quartz. (*Gen. Elec. Lamp Bulletin* LD-1.)

DEFINITION OF SUNLAMP

Ultraviolet lamps which are used for therapy are known to the public as sunlamps. The term sunlamp, however, has a very specific meaning and should not be applied to ultraviolet lamps indiscriminately.

The council of Physical Therapy of the American Medical Association [7] defines a sunlamp as a lamp that, at a specified distance, emits ultraviolet radiation not differing essentially from that of the clearest weather, midday, midsummer, mid-latitude, sea level, natural sunlight, in total intensity and in spectral range of wavelengths extending from about 2900 A to and including 3130 A and does not emit an appreciable amount of ultraviolet of wavelengths shorter than 2800 A. The erythemal reaction has been adopted as a basis for judging the effectiveness of a sunlamp.

The specifications for the minimum intensity of sunlamps set by the Council of Physical Therapy are based on a comfortable and convenient

TABLE 5

PER CENT OF ENERGY INPUT RADIATED IN VARIOUS SPECTRAL REGIONS FROM A BARE UVIARC

Arc designation	UA-2
Arc current	3.1 amp
Arc watts	250
Arc length	7.5 cm
Arc diameter	1.7 cm

Wavelength Band in Angstroms	Per Cent of Arc Input *	Wavelength Band in Angstroms	Per Cent of Arc Input *
5800–7600	0.44	3300–3400	0.268
5700–5800	2.0	3200–3300	0.128
5500–5700	0.064	3100–3200	2.12
5400–5500	1.82	3000–3100	1.02
4400–5400	0.39	2900–3000	0.60
4300–4400	1.59	2800–2900	0.41
4100–4300	0.136	2700–2800	0.375
4000–4100	0.98	2600–2700	1.08
3800–4000	0.088	2500–2600	1.79
3700–3800	0.06	2400–2500	0.665
3600–3700	2.81	2300–2400	0.64
3500–3600	0.048	2200–2300	0.163
3400–3500	0.068		

Total ultraviolet less than 3800 A	12.2%
Visible, 3800–7600 A	7.5%
E-vitons	803,400

* Calculated from *Gen. Elec. Lamp Bulletin* LD-1.

operating distance of 24 in. from the front edge of the reflector. The minimum intensity of the lamp must be such that the time of exposure required to produce minimum perceptible erythema will not be over 15 min for a therapeutic lamp or over 60 min for a sunlamp. This specification protects the public against both lamps emitting excessive amounts of ultraviolet and lamps which do not emit significant amounts of ultraviolet.

In addition, the specification requires that at no point within a circle 18 in. in diameter at a distance of 24 in. from the front of the reflector shall the intensity be less than one-third of the average value in the central 0–5°.

MERCURY VAPOR SUNLAMPS

Since all mercury vapor arcs emit considerable radiation of shorter wavelength than 2800 A, it is necessary to filter out this radiation in

order to make them conform to the above definition of sunlamps. This can be done by filtering the light from an intermediate-pressure quartz mercury lamp with a glass which does not transmit radiation below 2800 A. Another alternative is to make the lamp envelope of the filter material.

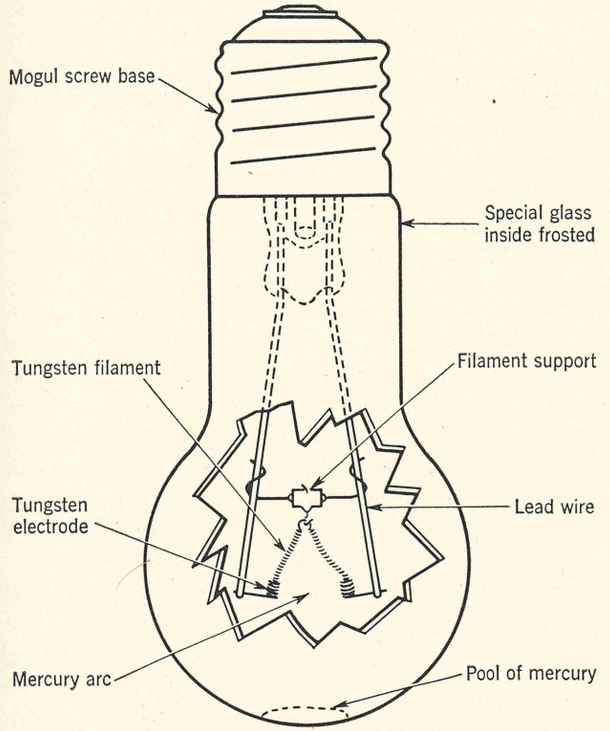


FIG. 13. Construction of S-1 Lamp. (*Gen. Elec. Lamp Bulletin* LD-1.)

One of the earliest sunlamps of this kind made for general use was an a-c operated lamp in a Corex bulb. This lamp has some ingenious features for starting and maintaining the arc. The structure is shown in Fig. 13. When voltage is applied, the filament heats up to a temperature of 3000°K. This is sufficient to give appreciable thermionic emission. As a result of the voltage drop across the filament, electrons emitted from the negative end pass across the space to the positive end. Since the voltage drop is greater than the ionization potential of mercury, the electrons passing between the ends of the filament produce ions and so initiate a discharge. The bombardment of the ends of the fila-

ment results in further heating and more thermionic emission so that very shortly an arc is started. Once started, the heat capacity of the heavy filament is sufficient to maintain it at a high enough temperature to emit enough electrons for the arc so that the latter will start readily on each half cycle. Thus in the initial stage of operation the arc takes place between the tungsten electrode and the opposite end of the filament and eventually takes place between the ends of the filament leads. The resistance of the arc is smaller than that of the filament so that it forms a shunt circuit with it, thus reducing the temperature of the filament during operation to about 2300°K.

The required mercury vapor pressure is attained first by the heat of the filament and then by that of the arc. In order to facilitate starting, the bulb contains a few millimeters of argon. Since the argon pressure is high compared with the initial vapor pressure of mercury vapor at room temperature (1 μ), the arc starts as an argon arc. As the bulb warms up and the mercury vapor pressure increases, since its ionizing potential is 10.39 compared with 15.86 for argon, and also because the probability of ionization is greater for mercury than for argon, the discharge soon shifts to the mercury and the argon lines are barely perceptible. Under normal conditions the mercury vapor pressure is about 0.9 atmosphere. The radiation then consists of that of a mercury arc plus the continuous spectrum of the incandescent tungsten electrodes. (These are not at uniform temperature but vary from 3250 to 2300°K.) This lamp operates on a high-reactance autotransformer.

Table 6 gives the spectral energy distribution of the radiation from an S-1, 400 watt, 0.9 atmosphere sunlamp enclosed in a bulb of No. 776 glass. The first column gives the watts radiated in various spectral regions. The second column expresses the watts in per cent of the overall input to the lamp and so gives a measure of its efficiency. The table shows that very little energy is radiated at wavelengths below 2800 A. This is to be expected on account of the cut-off of the No. 776 glass which cuts out most of the 2804 A line and practically eliminates the strong 2537 A line. The ultraviolet transmission of No. 776 glass at the operating temperature of the lamp is less than half as much as at room temperature.* The percentage of energy radiated in the visible spectrum is high compared with the ultraviolet on account of the radiation from the incandescent tungsten electrodes.

The lower part of the table is an appraisal of the effectiveness of the radiation for killing bacteria and for producing erythema. The germicidal effectiveness is expressed as the equivalent milliwatts at 2600 A which would have the same killing effect on bacteria as the emitted radiation. This value is small for the S-1 lamp because almost all the short-wave radiation which is most effective in killing bacteria is filtered out.

The erythemal flux at wavelengths greater than 2800 A is expressed in terms of E-vitons (where 1 E-viton is the equivalent of 10 μw at 2967 A). The erythemal flux has been separated into the portion above and below the wavelength 2800 A. The reason for this separation is that the antirachitic effectiveness has been shown to coincide very closely with the erythemal effectiveness at wavelengths greater than 2800 A. Accordingly, the erythemal effectiveness for wavelengths longer than 2800 A is also a measure of the antirachitic effectiveness. Below 2800 A, however, the relationship is not quite so close. The table shows that the S-1 is a very powerful erythemal source in the antirachitic region.

The energy in microwatts in various spectral regions falling on a square centimeter of surface at a distance of 1 meter from the lamp is given in the last column of the table.

* Private communication, Dr. B. T. Barnes.

TABLE 6

RADIATION FROM S-1 SUNLAMP *

Lamp watts	400
Lamp operating volts	14
Lamp operating current	30
Pressure, atmospheres	0.9
Bulb, No. 776 glass	

	Watts Radiated	Per Cent of Lamp Watts	Microwatts/cm² † at 1 Meter from Lamp
Below 2800 A	0.01	0.002	1.2
2800–3200 A	3.2	0.8	214
3200–3800 A	4.5	1.1	396 (3200–3700 A)
Total UV below 3800 A	7.7	1.95	
Total visible 3800–7600 A	45	11	

Germicidal effectiveness, equivalent milliwatts at 2600 A	66
Erythemal flux	
above 2800 A, E-vitons	67,720
below 2800 A, equivalent E-vitons	280

* *Gen. Elec. Lamp Bulletin* LD-1.

† Calculated from M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946, page 85.

The energy distribution is shown in greater detail in Table 6A which gives the intensity in microwatts per square centimeter falling on a surface at a distance of 1 meter from the lamp due to some of the stronger lines.

TABLE 6A *

Wavelength in Angstroms	Microwatts/cm^2 at 1 Meter †
2537	0.11
2652	0.35
2804	1.5
2894	2.3
2967	11.5
3022	28.4
3129	105

* Calculated from W. E. Forsythe, B. T. Barnes, and M. A. Easley, *J. Optical Soc. Am.*, **24**, 178 (1934).

† On axis of reflector. Reflector axis 30° from vertical.

High-Pressure Mercury Lamps. General Characteristics

In the course of the search for efficient illuminants, great progress was made in the development of high-pressure mercury lamps. These have proved to be useful sources of ultraviolet as well as of visible radiation.

One of the fundamental characteristics of high-pressure arcs is the high temperature of the gas and the thermal equilibrium between the gas and the electrons. The temperatures range from 5500 to 8000°K.

High-pressure arcs also differ from low-pressure arcs in the voltage gradient of the positive column. This is much larger for the high- than for the low-pressure lamps. This results in a much greater energy input per unit length of the lamp and consequent heating of the lamp envelope. DeGroot has shown that the voltage gradient in the mercury arc column is related to the pressure by the empirical equation

$$P_{\text{atm}} = \frac{G - 100}{3}$$

where G is the gradient in the lamp in volts per centimeter. This formula has been tested for lamps 2 mm in diameter up to 150 atmospheres. By means of this relation it is a simple matter to determine the pressure of a high-pressure mercury arc from the volts per unit length of the arc column. This formula applies only to the super high-pressure lamps.

At high pressures the arc stream is greatly constricted. These constricted arcs are only very slightly affected by the tube walls. The diameter of the tube may be made as small as is consistent with keeping the walls at a safe operating temperature. In some cases the operating position is limited to the vertical on account of convection currents which force the arc against the tube wall, causing erosion.

Thus high-pressure arcs are characterized by a very brilliant small-diameter arc operating at a relatively large current density and high voltage. Since the voltage gradient in the arc increases with pressure, the high-pressure arcs are shorter than low-pressure arcs at the same voltage. They also have a smaller tube diameter if this does not make the wall temperature excessively high.

The spectrum of a high-pressure arc shows a broadening of the lines with increasing pressure and a continuous background which also increases with increasing pressure. The pressure broadening of the lines is greater on the side towards the red than towards the blue.

In general, as the pressure is increased the brightness of the continuous background increases. These features of high-pressure arcs are illustrated in Fig. 14 which shows the spectral energy distribution [8] in a high-pressure lamp at pressures of 31, 75, 165, and 285 atmospheres.

As the pressure is increased the peaks of the lines become lower while the intensity of the continuous background increases. At 285 atmospheres, as shown in 14*D*, practically all trace of the line character of the spectrum has disappeared.

In practice these lamps take the form of small-diameter, heavy-wall quartz tubes, and for this reason they are often called "capillary"-type lamps. They are usually enclosed in an outer jacket of glass which serves the threefold purpose of filter, heat insulator, and shield in case of breakage of the arc tube. Operating pressures range from 2 atmospheres for air-cooled lamps to 110 atmospheres for water-cooled lamps.

Cathodes are usually of the thorium self-heated type to facilitate easy starting and reduce cathode sputtering. An auxiliary electrode is also used to aid in starting. A typical lamp is shown in Fig. 15. When voltage is applied the discharge first takes place between the starting electrode and the nearer of the operating electrodes because of the close spacing. The current in this discharge is limited to a small value by a high series resistance. Once this auxiliary discharge has liberated a few ions and electrons, the arc readily jumps to the operating electrode. Lamps of this type are usually operated on alternating current on a high-reactance transformer. This supplies an initial high voltage

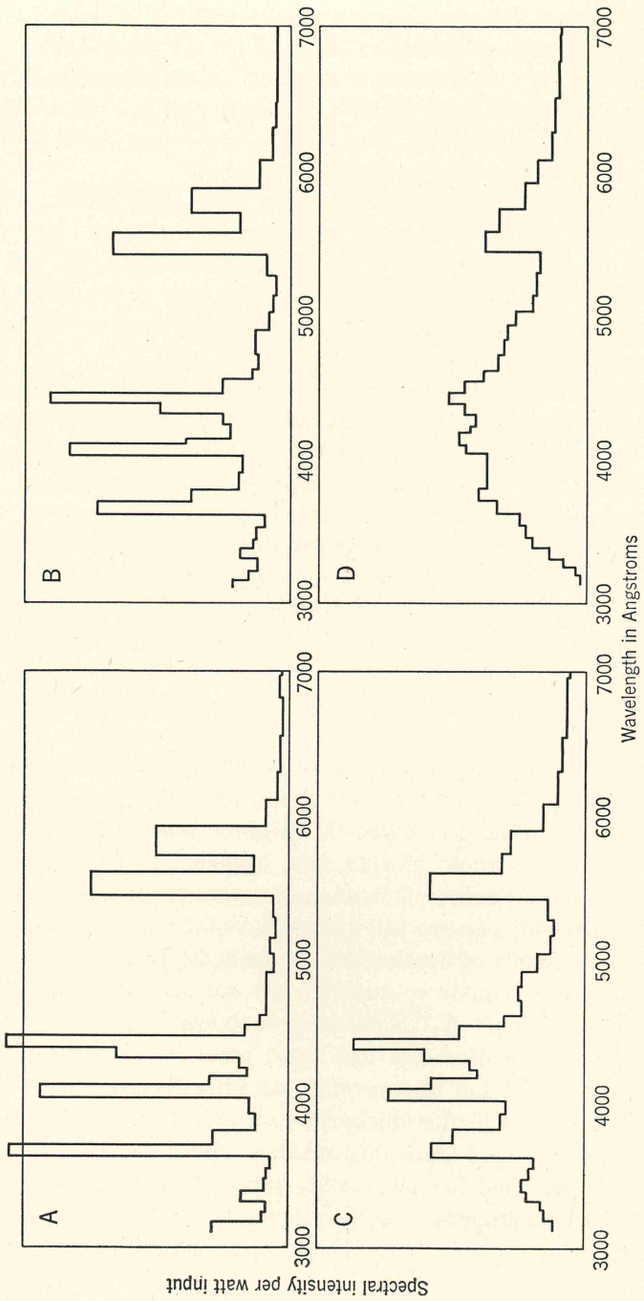


FIG. 14. Emission spectrum of high-pressure mercury arc lamp showing continuous background. *A*. 31 atmospheres. *B*. 75 atmospheres. *C*. 165 atmospheres. *D*. 285 atmospheres. (E. B. Noel, *Illum. Eng.*, **36**, 243, 1941.)

for starting and a ballast reactance to compensate for the negative volt ampere characteristic of the arc.

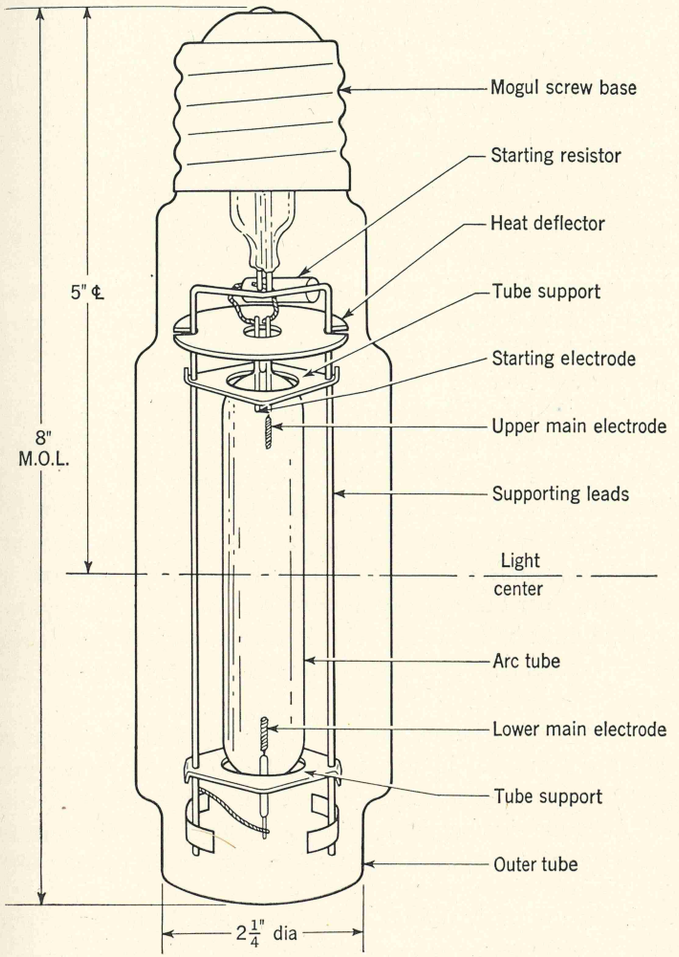


FIG. 15. Construction of a typical high-pressure mercury arc. (Courtesy of General Electric Co.)

The same basic capillary unit is used in several different kinds of envelopes to make lamps suited for various applications. For example, for sunlamp purposes the envelope is of glass which transmits practically all the visible and the ultraviolet radiation down to wavelength 2800 A.

Thus it passes practically all the lamp radiation longer than 2800 A. Where the lamp is to be used for illumination and the erythemal radiation is not desired, the bulb is made of glass which cuts off all radiation of shorter wavelength than 3000 A.

For producing fluorescent effects, use is made of the 3650 A line. This is one of the strongest lines in the mercury spectrum and is very effective in exciting fluorescence in many substances. To make use of it for this purpose, it is essential to eliminate nearly all visible radiation. Accordingly, the lamp is enclosed in a bulb of red-purple Corex. This kind of lamp is popularly known as a "black-light lamp."

The same type of "capillary" arc is also used as a sunlamp in a bulb in which is incorporated an aluminum reflector. The character of the radiation is essentially the same, but its spatial distribution is altered. This type of lamp is useful where it is desired to project the ultraviolet or where a high-intensity per unit area is required. It may be combined with an external filter for "black-light" effects.

All the arcs just described require ballast or auxiliaries of some kind. Lamps have also been developed in which the ballast is an integral part of the lamp. The ultraviolet source is a capillary arc, and the ballast is a series tungsten filament incorporated in the same protecting bulb. This type of lamp may be used directly in any ordinary household lighting socket. Since this series combination does not operate from a high-voltage transformer but must operate on the line voltage, the arc operating voltage must be reduced. This is accomplished by decreasing the pressure. Accordingly, this type of lamp is operated at about 2 atmospheres.

A number of other lamps have been developed of this same general type differing somewhat in size, bulb material, and operating pressure, but operating on the same general principles. They will be discussed in detail in the following sections. Several lamps quite different in outward form but all based on a capillary arc are shown in Fig. 16.

Characteristics of Various High-Pressure Mercury Arcs

Tables 7 to 10 show the energy distribution from four lamps, all of which use the same basic quartz capillary. The output, however, is filtered through different kinds of bulbs to adapt it to various purposes. The construction of the capillary unit has been shown in Fig. 15.

The S-4 is a sunlamp and is enclosed in a bulb of glass which cuts off radiation below 2800 A but transmits as much as possible in the 2800–3200 A range.

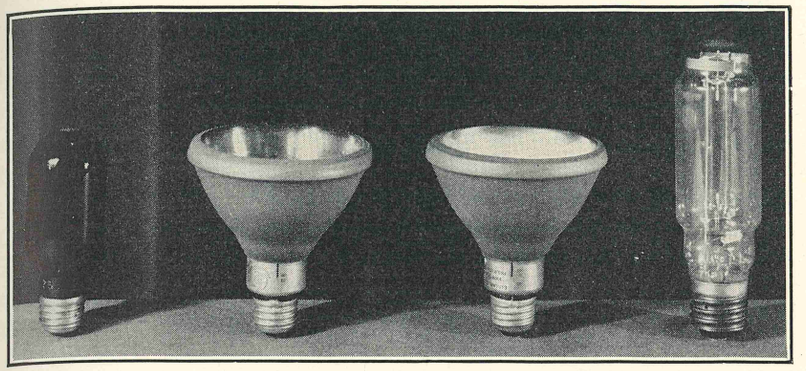


Fig. 16. High-pressure mercury lamps using the same type of arc in different types of bulbs. (Courtesy of General Electric Co.)

Table 7 gives the spectral energy distribution of the radiation from this lamp. The second column of the table shows that the *amount* of energy radiated in the various regions of the ultraviolet is somewhat less than for the S-1 sunlamp (Table 6). The third column of the table, however, shows that the high-pressure lamp is two to three times as

TABLE 7

Radiation from S-4 Sunlamp *

Lamp watts	100
Lamp operating volts	130
Lamp operating current	0.9
Pressure, atmospheres	8
Bulb, quartz capillary in No. 721 glass	

	Watts Radiated	Per Cent of Lamp Watts	Microwatts/cm² † at 1 Meter from Lamp	
Below 2800 A	0.01	0.01	1.5	
2800–3200 A	2.1	2.1	190	
3200–3800 A	3.6	3.6	642	(3200–3800 A)
Total UV below 3800 A	5.7	5.7		
Total visible 3800–7600 A	13.2	13.2		

Germicidal effectiveness, equivalent milliwatts at 2600 A	71
Erythemal flux	
above 2800 A, E-vitons	49,925
below 2800 A, equivalent E-vitons	75

* *Gen. Elec. Lamp Bulletin* LD-1.

† M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946, page 85.

efficient in producing this ultraviolet energy as the S-1. The essential difference in output between the two lamps is that the S-1 radiates more energy in the visible and infrared on account of the high temperature of its incandescent electrodes.

Both lamps are quite low in germicidal effectiveness because the glass cuts off all the germicidally effective radiation below 2800 A. The S-4 is about 25 per cent lower in erythemal flux than the S-1.

The last column shows the energy in the various spectral regions in microwatts per square centimeter on a surface at a distance of 1 meter from a bare lamp. This again shows that the S-4 is the approximate equivalent of the S-1 except for the large visible and infrared output of the latter.

The A-H4 lamp is intended for uses other than therapy. Accordingly, it is enclosed in an outer bulb of glass which does not transmit any of the radiation below 3000 A. Its erythemal flux is almost negligible. Its spectral energy distribution is shown in Table 8.

TABLE 8

RADIATION FROM A-H4 CAPILLARY LAMP *

Lamp watts	100
Lamp operating volts	130
Lamp operating current	0.9
Pressure, atmospheres	8
Bulb, quartz capillary in No. 772 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0.72	0.72
3200–3800 A	4.3	4.3
Total UV below 3800 A	5.0	5.0
Total visible 3800–7600 A	10.4	10.4
Germicidal effectiveness, equivalent milliwatts at 2600 A		0
Erythemal flux above 2800 A, E-vitons		3300
Erythemal flux below 2800 A, equivalent E-vitons		0

* *Gen. Elec. Lamp Bulletin* LD-1.

The B-H4 lamp is intended for the production of fluorescent effects, so-called black-light effects. These require radiation in the range 3200–3800 A. The mercury lines in this region are 3342 A and 3650 A, of which the 3650 A line is about 10 times the stronger. The visible

radiation from the lamp must be practically entirely eliminated, because the fluorescent radiation produced by ultraviolet radiation is usually low in intensity compared with the visible radiation coming directly from the lamp. Accordingly, the lamp is enclosed in a bulb of glass which filters out all the visible radiation and transmits relatively little except the 3650 A line. As the transmission of the glass at this wavelength is only about 29 per cent at room temperature and even less at wavelengths just above and just below this, the energy radiated in the 3200–3800 A band is only about one-quarter of that from the S-4. The transmission of the glass is even less at the operating temperature of the lamp. The characteristics of this lamp are shown in Table 9.

TABLE 9

RADIATION FROM B-H4 CAPILLARY BLACK-LIGHT LAMP *

Lamp watts	100
Lamp operating volts	130
Lamp operating current	0.9
Pressure, atmospheres	8
Bulb, quartz capillary in No. 5872 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0.001	0.001
3200–3800 A	0.83	0.83
Total UV below 3800 A	0.83	0.83
Total visible 3800–7600A	0.06	0.06
Germicidal effectiveness, equivalent milliwatts at 2600 A		0
Erythemal flux above 2800 A, E-vitons		18
Erythemal flux below 2800 A, equivalent E-vitons		0

* *Gen. Elec. Lamp Bulletin* LD-1.

The RS-4 uses the same basic capillary unit as the S-4, but it is enclosed in a reflector-type bulb so that the beam can be projected. The heavy cover glass of the front of the bulb absorbs more of the radiation than the thin-walled bulb used in the S-4. Consequently, although the energy distribution is about the same as for the S-4, all values are reduced by approximately 25 per cent. In spite of this, however, high intensities may be obtained directly in the path of the beam because of the focusing and directive action of the reflector. The characteristics of this lamp are shown in Table 10.

TABLE 10

RADIATION FROM RS-4 CAPILLARY SUNLAMP *

Lamp watts	100
Lamp operating volts	130
Lamp operating current	0.9
Pressure, atmospheres	8
Bulb, quartz capillary in No. 772 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0.01	0.01
2800–3200 A	1.5	1.5
3200–3800 A	2.9	2.9
Total UV below 3800 A	4.4	4.4
Total visible 3800–7600 A	9.6	9.6
Germicidal effectiveness, equivalent milliwatts at 2600 A		59
Erythemal flux above 2800 A, E-vitons		35,000
below 2800 A, equivalent E-vitons		...

* *Gen. Elec. Lamp Bulletin* LD-1.

The RS lamp is also a sunlamp employing a capillary arc in a reflector-type bulb. This is made of glass which transmits the radiation in the erythemal region. This lamp incorporates a tungsten filament ballast within the reflector bulb, so that essentially a capillary arc and a tungsten filament lamp connected in series are operated inside the same bulb. Accordingly, no auxiliary ballast is required and the lamp can be screwed into an ordinary light socket. In order to operate on any house line voltage the arc voltage must be reduced. This is done by designing the RS lamp capillary to operate at a pressure of about 2 atmospheres instead of 8, as in the other lamps just discussed. The RS characteristics are shown in Table 11.

The angular distribution of energy in the beam of the RS lamp is shown in the diagram of Fig. 17. This shows the relative energy expressed in E-vitons at various angles about the axis of the lamp. As can be seen from the figure, at 25° from the axis the intensity is about half of the maximum value. The intensity varies inversely as the square of the distance from the lamp. The maximum value at a distance of 30 in. from the lamp is approximately 5.4 E-vitons per cm². Since the exposure required for a just perceptible erythema is 42 E-viton min per

TABLE 11

RADIATION FROM RS FILAMENT BALLAST CAPILLARY SUNLAMP *

Lamp watts	275
Lamp operating volts	110–125
Lamp operating current	2.5
Pressure, atmospheres	2
Bulb, quartz capillary in No. 776 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0.01	0.003
2800–3200 A	1.7	0.61
3200–3800 A	3.4	1.2
Total UV below 3800 A	5.1	1.9
Total visible 3800–7600 A	7.6	2.8
Germicidal effectiveness, equivalent milliwatts at 2600 A		60
Erythemal flux E-vitons		35,000

* *Gen. Elec. Lamp Bulletin* LD-1.

cm², an exposure of the skin on the axis of the lamp at a distance of 30 in. from the lamp for about 8 min would be required.

WATER-COOLED LAMP

Operation at pressures above a few atmospheres involves an increased gradient, which consequently results in higher temperatures of the quartz bulb wall. In order to prevent it from overheating and softening, some means of cooling other than radiation and natural convection must be supplied for lamps intended to be operated at very high pressures. Consequently, lamps for the higher pressures are either water cooled or cooled by forced air circulation. The water must be circulated sufficiently rapidly to prevent the formation of steam bubbles on the surface of the quartz tube. This is accomplished by circulating the water at a very high velocity. The purity of the water supply is important if the lamp is to be used for radiation of shorter wavelength than 2800 A. The purity of the water is also important in order to minimize the conductivity between the ends of the lamp.

The A-H6 which is shown in Fig. 18 is a water-cooled high-pressure capillary arc operating at a pressure of 110 atmospheres. As a result of the high pressure and consequent high gradient, the lamp operating

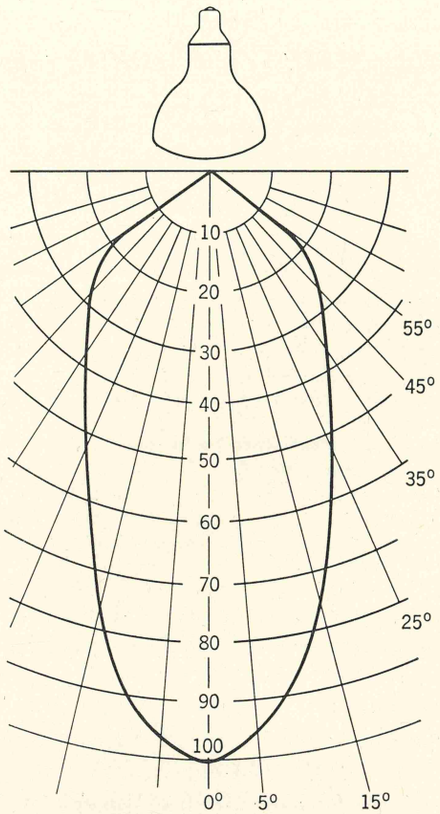


FIG. 17. Angular distribution of energy in the beam of the RS lamp. (*Gen. Elec. Lamp Bulletin* LD-1.)

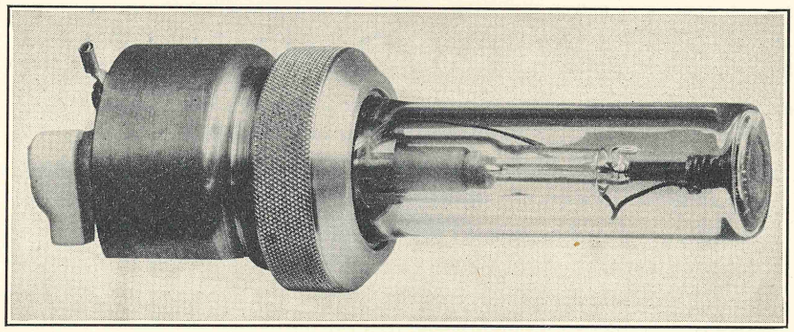


FIG. 18. Water-cooled high-pressure (110 atmospheres) mercury arc showing lamp in water jacket. (Courtesy of General Electric Co.)

TABLE 12

RADIATION FROM A-H6 WATER-COOLED CAPILLARY LAMP IN QUARTZ *

Lamp watts	1000
Lamp operating volts	840
Lamp operating current	1.4
Pressure, atmospheres	110
Bulb, quartz	

	Watts Radiated	Per cent of Lamp Watts	Microwatts/cm² † at 1 Meter
Below 2800 A	31	3.1	256
2800–3200 A	75	7.5	738
3200–3800 A	90	9.0	648 (3200–3700 A)
Total UV below 3800 A	195	19.5	
Total visible 3800–7600 A	290	29	

Germicidal effectiveness, equivalent milliwatts at 2600 A	32,000
Erythemal flux	
above 2800 A, E-vitons	2,255,000
below 2800 A, equivalent E-vitons	950,000

* *Gen. Elec. Lamp Bulletin* LD-1.

† Calculated from M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946, page 85.

voltage is 840 volts. Its energy distribution is shown in Table 12. This lamp is one of the most powerful available sources of ultraviolet throughout the entire spectrum, partly because of its high efficiency and partly because of its high wattage. A 1000-watt A-H6 radiates 31 watts of energy at less than 2800 A, whereas the next most powerful source of short-wave ultraviolet, the 30-watt germicidal lamp, radiates 7.2 watts in the same range. The germicidal lamp is actually the more efficient of the two in this region, but because of the nature of the low-pressure arc it cannot easily be made in large units. At wavelengths greater than 2800 A the A-H6 is more efficient than any other mercury sources. Since the arc is water cooled, the ultraviolet is accompanied by less heat than that from any other source. Its characteristics are similar when the lamp is cooled by jets of high-velocity air. Under these conditions the input is reduced to 900 watts and the lamp is designated as the B-H6.

The A-H6 is enclosed in a bulb of No. 774 glass when the short-wave ultraviolet is not required. Its characteristics are given in Table 12*A*. It is a very intense source of visible radiation as is evident from the table. It radiates more than twice as much energy in the visible

TABLE 12*A*

RADIATION FROM A-H6 WATER-COOLED CAPILLARY LAMP IN GLASS *

Lamp watts	1000
Lamp operating volts	840
Lamp operating current	1.4
Pressure, atmospheres	110
Bulb, No. 774 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	6.8	0.68
3200–3800 A	62	6.2
Total UV below 3800 A	69	6.9
Total visible 3800–7600 A	290	29
Germicidal effectiveness, equivalent milliwatts at 2600 A		68
Erythemal flux above 2800 A, E-vitons		90,000
Erythemal flux below 2800 A, equivalent E-vitons		0

* *Gen. Elec. Lamp Bulletin* LD-1.

spectrum as a 1000-watt tungsten incandescent lamp. The brightness of its central core is 190,000 candles per sq in., about one-fifth the brightness of the sun.

The characteristics of two other mercury arcs which operate at somewhat lower pressures are given in Tables 13 and 14. These lamps, the A-H1 and the A-H9, operate at pressures of 1.2 and 0.7 atmospheres, respectively. They are designed for general lighting applications, but they also radiate significant amounts of near ultraviolet.

Table 15 gives the characteristics of the A-H5. This lamp has a very high output of near ultraviolet in the range 3200–3800 A. It is useful for producing fluorescent effects, if it is enclosed in a filter which will absorb the visible radiation.

Table 16 gives the characteristics of the E-H4. This uses the same basic capillary as the S-4 sunlamp, but it is enclosed in a reflector-type flood lamp bulb. It is useful for producing fluorescent effects when combined with a filter to remove the visible radiation.

LOW-PRESSURE LAMPS

As the vapor pressure of mercury in a discharge is reduced the intensity of the 2537 A line, known as the mercury resonance line, in-

TABLE 13

RADIATION FROM A-H1 CAPILLARY MERCURY ARC *

Lamp watts	400
Lamp operating volts	137
Lamp operating current	3.2
Pressure, atmospheres	1.2
Bulb, No. 772 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0.001	0.0003
3200–3800 A	4.3	1.1
Total UV below 3800 A	4.3	1.1
Total visible 3800–7600 A	44	11
Germicidal effectiveness, equivalent milliwatts at 2600 A		0
Erythemal flux above 2800 A, E-vitons		450
Erythemal flux below 2800 A, equivalent E-vitons		0

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 14

RADIATION FROM A-H9 MERCURY ARC *

Lamp watts	3000
Lamp operating volts	535
Lamp operating current	6.1
Pressure, atmospheres	0.7
Bulb, No. 172 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0	0
3200–3800 A	22	0.72
Total UV below 3800 A	22	0.72
Total visible 3800–7600 A	370	12.5
Germicidal effectiveness, equivalent milliwatts at 2600 A		0
Erythemal flux above 2800 A, E-vitons		2200
Erythemal flux below 2800 A, equivalent E-vitons		0

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 15

RADIATION FROM A-H5 CAPILLARY MERCURY ARC *

Lamp watts	250
Lamp operating volts	135
Lamp operating current	2.1
Pressure, atmospheres	4
Bulb, No. 774 glass	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0.005	0.002
3200–3800 A	6.6	2.6
Total UV below 3800 A	6.6	2.6
Total visible 3800–7600 A	32.9	13.2

Germicidal effectiveness, equivalent milliwatts at 2600 A	0
Erythemal flux above 2800 A, E-vitons	680
Erythemal flux below 2800 A, equivalent E-vitons	0

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 16

RADIATION FROM E-H4 CAPILLARY MERCURY ARC *

Lamp watts	100
Lamp operating volts	130
Lamp operating current	0.9
Pressure, atmospheres	8
Bulb, quartz capillary in No. 776 glass	
Parabolic aluminum reflector	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0	0
2800–3200 A	0.05	0.05
3200–3800 A	2.2	2.2
Total UV below 3800 A	2.2	2.2
Total visible 3800–7600 A	7.8	7.8

Germicidal effectiveness, equivalent milliwatts at 2600 A	0
Erythemal flux above 2800 A, E-vitons	200
Erythemal flux below 2800 A, equivalent E-vitons	0

* *Gen. Elec. Lamp Bulletin* LD-1.

creases markedly. This fact is made use of in the construction of low-pressure lamps which emit this radiation almost exclusively.

The radiation of certain frequencies known as resonance radiation is the result of a transition of an atom from the lowest excited state to the normal state. This radiation may be reabsorbed by another atom with which it "collides." This atom in turn may reemit the radiation, and in this way the radiation may be passed from atom to atom before it finally escapes from the arc. If the gas pressure is high, the mean free path of the radiation will be small and the radiation will undergo many such transitions. During this process, there is a strong probability that one of the atoms while in the excited-resonance state may collide with an electron which has sufficient energy to ionize it or to raise it to a higher excited state. In either case the radiation emitted as the atom returns to its normal state will be of a frequency other than the resonance frequency. Thus the resonance radiation is effectively lost. The only atoms effective in emitting resonance radiation which gets out of the lamp are those that are at the outer layer of the discharge. The higher the pressure, however, the less is the probability of the resonance radiation gaining this outer layer without making a collision which results in its transformation. Thus the maximum output of resonance radiation will be obtained under conditions which favor the existence of the largest number of atoms excited to the resonance state close to the wall of the bulb. This implies a low-pressure discharge. At high pressures the concentration of atoms in the resonance state may be large in the discharge, but the probability of the radiation reaching the bulb before making a collision is small. On the other hand, at extremely low pressures the number of atoms available to be put into the excited state becomes very small.

The concentration of atoms and the vapor pressure, of course, depend on the temperature of the bulb wall. Figure 19 shows how the efficiency for the production of resonance radiation passes through a maximum with increasing wall temperature. For a 1-in. diameter tube the optimum efficiency occurs at a temperature of 40°C, corresponding to a vapor pressure of 6 μ.

The resonance radiation is produced most efficiently in the positive column; hence as much of the lamp voltage as possible is used in this part of the discharge. This involves making a lamp which is long compared with its diameter. Hence lamps of this type are usually in the form of long tubes.

The low-pressure lamp is inherently a source of low intrinsic brilliancy because of its large surface. Accordingly, although it is highly

efficient for the production of resonance radiation, it is not well suited for applications where a concentrated source is required. A 30-watt germicidal lamp radiates as much as 24 per cent of the energy input to the lamp in the 2537 A line.

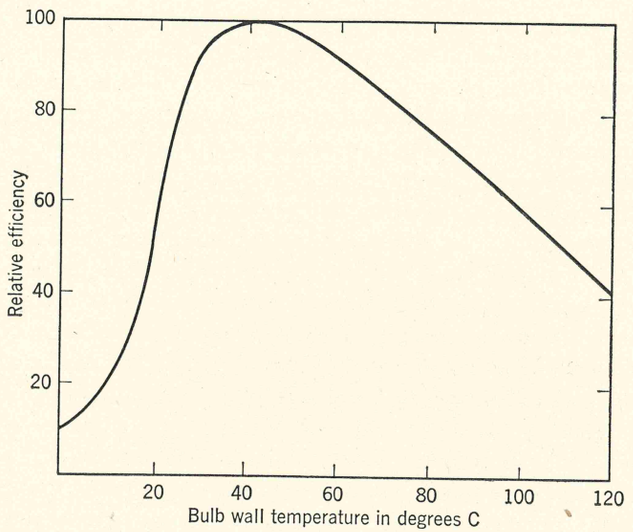


FIG. 19. Relative efficiency of production of mercury resonance radiation (2537 A) for different temperatures of the tube wall for a discharge tube 1 in. in diameter. (W. E. Forsythe, *Denison Univ. Bull.* XXVI, 13, 1941.)

Lamps of this general character in bulbs of ultraviolet glass are marketed under a variety of names. Germicidal lamps are hot-cathode lamps and operate at relatively low voltage. Sterilamps * are cold-cathode lamps and operate at relatively higher voltages. Low-pressure lamps in quartz bulbs are sometimes called cold quartz lamps. Regardless of the details of construction, all mercury vapor lamps operating at low bulb temperatures (and consequently low pressures) are sources almost exclusively of 2537 A radiation.

GERMICIDAL LAMPS

The characteristics of germicidal lamps are shown in Tables 17, 18, 19, and 20. They are very similar in physical form to the corresponding sizes of ordinary fluorescent lamps and have exactly the same electrical characteristics. From the tables it can be seen that they are

* Trademark registered at U. S. Patent Office.

TABLE 17

RADIATION FROM A 30-WATT LOW-PRESSURE (GERMICIDAL) LAMP *

Lamp watts	30
Lamp operating volts	103
Lamp operating current	0.34
Bulb, No. 9741 glass	
Length, 36 in.	
Diameter, 1 in.	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	7.2	24
2800–3200 A	0.16	0.53
3200–3800 A	0.13	0.42
Total UV below 3800 A	7.5	25
Total visible 3800–7600 A	0.65	2.15

Germicidal effectiveness, equivalent milliwatts at 2600 A	7,050
Erythemal flux	
above 2800 A, E-vitons	3,500
below 2800 A, equivalent E-vitons	396,500
Microwatts/cm^2 2537 A at 1 meter from lamp	67–78

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 18

RADIATION FROM A 15-WATT LOW-PRESSURE (GERMICIDAL) LAMP *

Lamp watts	15
Lamp operating volts	56
Lamp operating current	0.30
Bulb, No. 9741 glass	
Length, 18 in.	
Diameter, 1 in.	

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	2.9	19
2800–3200 A	0.06	0.42
3200–3800 A	0.05	0.34
Total UV below 3800 A	3.0	20
Total visible 3800–7600 A	0.26	1.75

Germicidal effectiveness, equivalent milliwatts at 2600 A	2,840
Erythemal flux	
above 2800 A, E-vitons	1,400
below 2800 A, equivalent E-vitons	158,600
Microwatts/cm^2 2537 A at 1 meter from lamp	27–31

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 19

RADIATION FROM AN 8-WATT LOW-PRESSURE (GERMICIDAL) LAMP *

Lamp watts 8
Lamp operating volts 54
Lamp operating current 0.18
Bulb, No. 9741 glass
Length 12 in.
Diameter, 5/8 in.

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	1.5	19
2800–3200 A	0.03	0.41
3200–3800 A	0.03	0.33
Total UV below 3800 A	1.6	20
Total visible 3800–7600 A	0.14	1.7
Germicidal effectiveness equivalent milliwatts at 2600 A		1,470
Erythemal flux above 2800 A, E-vitons		750
Erythemal flux below 2800 A, equivalent E-vitons		84,250
Microwatts/cm^2 2537 A at 1 meter from lamp		23–28

* *Gen. Elec. Lamp Bulletin* LD-1.

TABLE 20

RADIATION FROM A 4-WATT LOW-PRESSURE (GERMICIDAL) LAMP *

Lamp watts 4
Lamp operating volts 58
Lamp operating current 0.08
Bulb, No. 9741 glass
Length, 5¾ in.
Diameter, ½ in.

	Watts Radiated	Per Cent of Lamp Watts
Below 2800 A	0.5	13
2800–3200 A	0.01	0.25
3200–3800 A	0.01	0.25
Total UV below 3800 A	0.52	13.5
Total visible 3800–7600 A	0.06	1.7
Germicidal effectiveness, equivalent milliwatts at 2600 A		490
Erythemal flux, E-vitons		40,000
Microwatts/cm^2 2537 A, at 1 meter from lamp		6.5

* *Gen. Elec. Lamp Bulletin* LD-1.

sources almost exclusively of 2537 A radiation. Figure 20 shows the form of four of these lamps.

The 15-watt germicidal lamp is a tubular lamp, 18 in. long and 1 in. in diameter with a hot cathode at either end. It operates at an arc current of 0.31 amp with a drop of 55 volts. It is designed to operate at a bulb-wall temperature of 40°C. Like all arcs it has a negative volt ampere characteristic and so is used in a circuit with a high-reactance

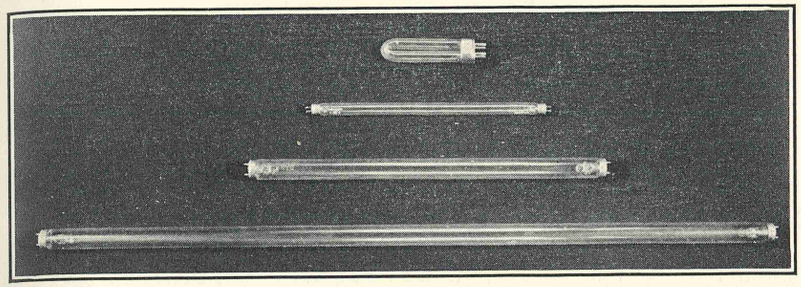


FIG. 20. Germicidal lamps (4-, 8-, 15-, and 30-watt sizes). (Courtesy of General Electric Co.)

ballast. It differs from a 15-watt fluorescent lamp only in being in a bulb which transmits ultraviolet and is not coated on the inside with fluorescent material.

The 30-watt lamp and the 8-watt lamp have the same operating characteristics and dimensions, respectively, as the corresponding fluorescent lamps.

The 4-watt lamp is the same in principle as the larger sizes, but the tube has been bent into a U-shape so that it provides the convenience of a single base lamp. This lamp has a length of 5¾ in. and a width of 1 in. Its output is about one-third that of the 8-watt lamp.

The characteristics of the radiation are quite similar for all four lamps. The total output increases slightly faster than the input watts on account of the increased efficiency of the larger sizes.

The tables show the extremely high efficiency of these lamps for the production of 2537 A radiation and the very low production of visible radiation. The former is higher and the latter lower than for any other type of mercury lamp. From these data it can be seen that for most practical purposes these lamps may be considered monochromatic sources of 2537 A, since more than 90 per cent of the energy radiated in the visible and the ultraviolet is concentrated in this one line.

In order to facilitate starting, the thermionic cathodes are heated be-

fore applying the arc voltage. This is done by means of the circuit shown in Fig. 21 which is identical with the one used for fluorescent lamps. The starting switch is closed. This short-circuits the cathodes through the ballast reactance which heats them to the normal operating temperature. In a few seconds, when they have come up to temperature, the switch is opened. This impresses the full line voltage across

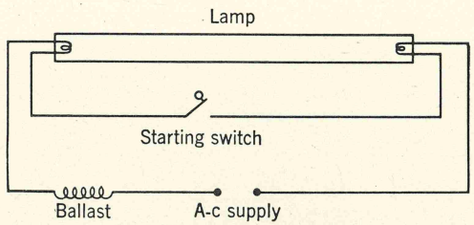


FIG. 21. Starting circuit for germicidal lamps.

the lamp. As the cathodes are now hot, they emit sufficient electrons to enable the arc to start. Once started, the arc current passing through the cathodes is sufficient to maintain them at the proper temperature. One of the several types of automatic starting devices usually used with fluorescent lamps is used instead of a manually operated switch.

These lamps may be operated on direct current (in a suitable circuit) but usually at the cost of a reduction in lamp life.

The bulb material commonly used is a glass which in 1-mm thickness has a transmission for 2537 A of about 65 per cent. It transmits longer wavelengths freely and cuts off in the neighborhood of 1850 A. This is evident from the very slight odor of ozone near these lamps compared with the large amount from similar lamps in quartz bulbs.

Table 21 gives data on a germicidal lamp which is designed for opera-

TABLE 21

T-6 SLIMLINE-TYPE GERMICIDAL LAMP *

Length 36 in. Diameter ¾ in.

Lamp watts	16	23	30	36
Lamp operating volts	150	135	115	105
Lamp operating current	120	200	300	420
Ultraviolet watts	6	8	10	11
Ultraviolet intensity in microwatts/cm² at 1 meter	65	90	110	120

* *Gen. Elec. Lamp Bulletin* LD-1.

tion at four different current ratings. This flexibility is attained by use of different ballast reactances. The efficiency is slightly reduced as the current is increased, but the ultraviolet output and efficiency are somewhat higher than for standard germicidal lamps. Low-pressure lamps are made in a great variety of other shapes to meet special requirements.

STERILAMPS

Table 22 gives the operating characteristics of cold-cathode Sterilamps.* These are low-pressure lamps and consequently have a spec-

TABLE 22 *

STERILAMP † OPERATING CHARACTERISTICS ‡

Lamp Designation	782L-30	782-20	782H-10	793
Rated watts	17	14	12	3.5
Overall length	34¾ in.	24¾ in.	14¾ in.	8⅛ in.
Starting voltage a-c	750	575	400	200
Operating voltage a-c	410	325	240	90
Operating current	0.050	0.055	0.060	0.040
Ultraviolet output in watts (2537 A)	5.2	2.0	2.0	0.13
Ultraviolet microwatts/cm² at 1 meter (2537 A)	46	20	20	1.3

* Westinghouse Data Sheet ACS-142.

† Trademark registered at U. S. Patent Office.

‡ These lamps are made in a number of glasses having the same transmission for 2537 A but having a transmission for 1849 A of 10 per cent, 1.5 per cent, and 0.1 per cent, respectively. Thus the quantity of ozone produced varies from a fairly large to a negligible amount.

trum in which the 2537 A line predominates. They differ from hot-cathode, low-pressure lamps (such as germicidal lamps) in that the electron emission from the cathode is produced by a high field at the surface of the cathode rather than by a high temperature. Accordingly, a filamentary type of cathode is not needed and the lamps have only a single terminal at each end. However, this kind of operation necessitates a higher voltage both for starting and for operating than is required for hot-cathode lamps of comparable dimensions. For example, a 15-watt, 18 in., hot-cathode lamp operates at 55 volts, whereas a 12-watt, 15-in., cold-cathode lamp operates at 240 volts (and requires 400 volts to start). This high voltage is supplied by a high-reactance transformer. In any application the simplicity in operation and longer life of the cold-cathode lamp must be balanced against the advantages

* Trademark registered at U. S. Patent Office.

of the low-voltage operation of the hot-cathode lamps. Cold-cathode construction is particularly well suited to long lamps.

Effect of Ambient Temperature

The effect of ambient temperature on low-pressure mercury vapor lamps is shown in Fig. 22. Curve *A* shows the ultraviolet output as a

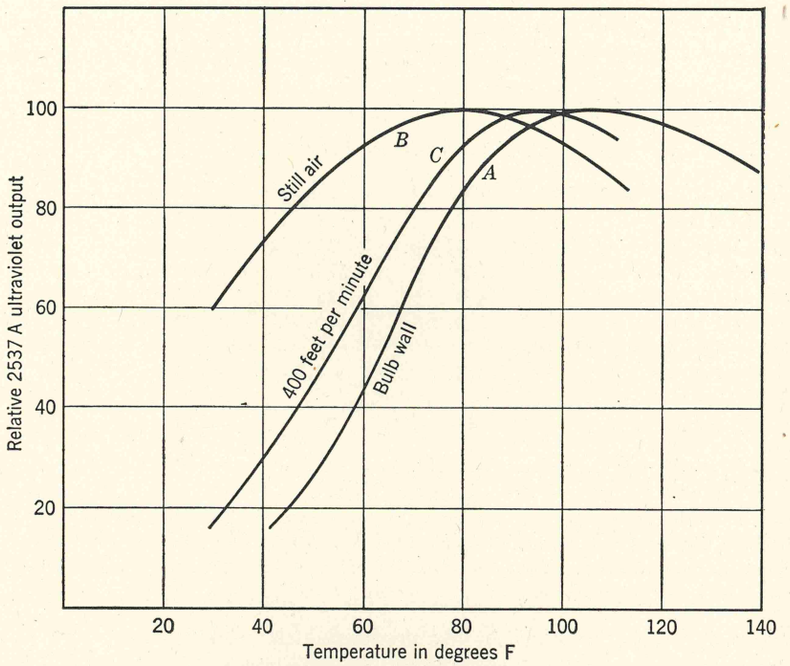


Fig. 22. Effect of ambient temperature on output of Sterilamps. (Westinghouse Electric Corp., Data Sheet ASC-159, 1951.)

function of bulb-wall temperature. Curve *B* shows the output as a function of air temperature in still air. Because of the electrical energy input to the lamp the bulb wall is actually considerably above ambient temperature. Accordingly, the still-air curve is displaced in the direction of lower temperatures. In moving air, as shown by *C*, the bulb temperature is less than in still air and the curve approaches the bulb-wall curve.

Glow Lamp

Where a low intensity of radiation is required and efficiency is not of primary importance, a cathodic type of discharge is used. This is a

discharge in which there is no positive column. As was noted on page 28, the positive column is not an essential part of an arc or glow discharge. If the electrodes are placed sufficiently close together, the positive column is eliminated. At the same time the voltage required to maintain it is also eliminated. A discharge of this type which is called

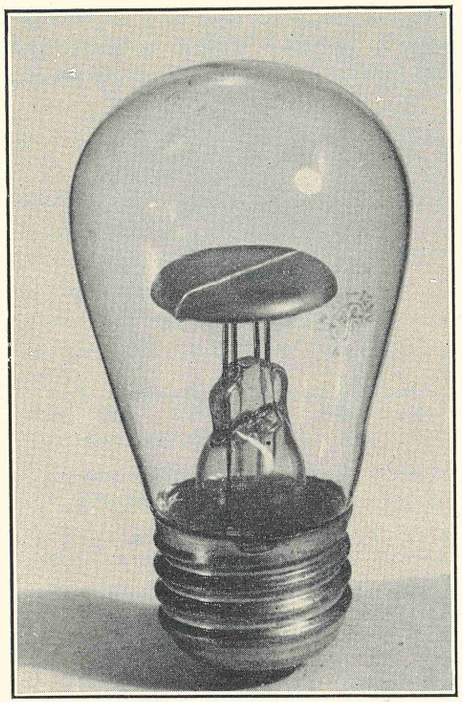


Fig. 23. Cathode glow lamp. (Courtesy of General Electric Co.)

a cathodic discharge can, accordingly, be operated at a lower voltage than a positive column discharge. This is made use of in many kinds of glow lamps where a small amount of radiation is required and operation at low voltage is more important than high efficiency. Most neon indicator lamps are of this kind.

Argon-filled glow lamps radiate a significant amount of near ultraviolet mostly in the neighborhood of 3300 A and relatively little in the visible spectrum. For this reason they are often used for exciting fluorescence in minerals. Since their output of visible radiation is low, they may be used without filters. A cathodic glow lamp is shown in Fig. 23.

Small cathodic glow lamps coated with BL phosphors (see Chapter 7) are used to excite the fluorescent markings on airplane instrument dials. Thus the instruments may be read, but the general level of illumination is kept low enough not to spoil the pilot's dark adaptation.

Black-Light Fluorescent Lamps

Low-pressure mercury arcs are also used to produce ultraviolet in the region around 3650 A, popularly known as black light. This radiation is very effective in exciting fluorescence in many substances. The inside

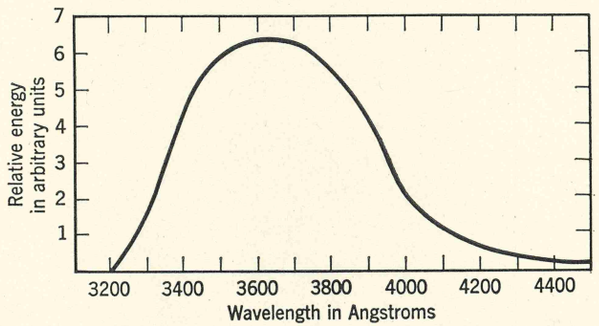


Fig. 24. Emission spectrum of cerium-activated calcium phosphate phosphor. (H. Froelich, *Trans. Electrochem. Soc.*, **91**, 241, 1947.)

wall of the black-light lamp is coated with a fluorescent substance, or phosphor, which absorbs 2537 A radiation and emits in a broad band around 3650 A. Thus the phosphor transforms 2537 A radiation into longer wavelength ultraviolet. The glass used does not transmit the short ultraviolet but allows the longer wavelengths to pass through. The phosphor used is a cerium-activated calcium phosphate. Its emission spectrum is shown in Fig. 24. These black-light phosphors are discussed more fully in Chapter 7.

Several sizes of lamps are made having the same construction, dimensions, and electrical characteristics as the corresponding sizes of fluorescent lamps. The energy distribution in the ultraviolet and visible spectrum for four different sizes of lamps is given in Table 23.

From the second column of the table it can be seen that the efficiency of the lamps increases significantly with increasing lamp wattage. This is characteristic of positive-column lamps.

The output of ultraviolet in the 3200–3800 A region is a greater percentage of the lamp input for these lamps than for any other kind of

TABLE 23

Spectral Energy Distribution for Black-Light (360 BL) Lamps *

Lamp		3200–3800 A		Total UV below 3800 A		Total Vis.	3800–7600 A	Erythemal
Watts	Length, Inches	W	% W	W	% W	W	% W	Flux
6	9	0.55	9.1	0.56	9.4	0.1	1.7	250
15	18	2.1	14.0	2.2	14.6	0.4	2.7	950
30	36	4.6	15.3	4.7	15.8	0.9	3.0	2100
40	48	6.7	16.8	6.9	17.3	1.5	3.8	3000

* *Gen. Elec. Lamp Bulletin* LD-1.

mercury discharge. The per cent of visible radiation is greater than that for germicidal lamps but is less than that of any of the sunlamps except the RS. Consequently, these lamps are very useful for producing fluorescent effects, blueprinting, and the like. They are almost insignificant sources of erythemal flux, because they emit practically no radiation of shorter wavelength than 3200 A.

Black-light fluorescent lamps are also made in the form of small cathode glow lamps and used for fluorescent instrument panel lighting on aircraft.

Summary of Mercury Arc Radiation Characteristics

From the previous discussion and the energy distribution tables, it can be seen that the most *efficient* source of radiation of less than 2800 A is the low-pressure mercury lamp. Where radiation of wavelength 2537 A is required in the absence of longer ultraviolet or visible radiation this lamp is particularly useful because of its low production of longer wavelengths.

The 1-atmosphere (360-watt UA-3) arc in quartz emits about twice as much 2537 A radiation as a 30-watt germicidal lamp (although at a much lower efficiency) as well as a high output of the other mercury lines. Because of its somewhat smaller dimensions it is a more concentrated source.

The various small quartz arcs emit long-wave ultraviolet comparable in amount with the 1-atmosphere quartz lamp. The ultraviolet is accompanied by a large amount of light. These lamps are convenient because of their small size and their insensitivity (due to the double bulb) to ambient temperature changes. Their small size makes them convenient for projection equipment.

The 1000-watt water-cooled arc emits more energy throughout the entire ultraviolet and visible spectrum than any other single unit and because of its small size has a higher intrinsic brilliancy. It is also more

efficient than any other mercury lamp except the germicidal for the production of 2537 A radiation.

Relative Production of Radiation in Various Wavelength Bands

The relative efficiencies of various types of mercury lamps for the production of radiation in specified wavelength bands is summarized in Table 24. The *only* criterion used here is that of efficiency, i.e., the

TABLE 24

Comparison of Mercury Lamps on the Basis of Efficiency *

Wavelength in Angstroms	Most Efficient	Second	Third	Fourth
	Lamps emitting no energy below 2800 A			
2800–3200	S-4	D-H1	S-1	A-H4
3200–3800	6–40-watt F	A-H6 (in glass)	D-H1	A-H4
	Including lamps emitting energy below 2800 A			
0–2800	Slimline	All sizes germicidal	Uviarc UA-2	A-H6
2800–3200	A-H6	Uviarc UA-2	Uviarc UA-3	Slimline
3200–3800	A-H6	Uviarc UA-2	Uviarc UA-3	Slimline

* *Gen. Elec. Lamp Bulletin* LD-1.

fraction of the input which is radiated in the various bands. The lamps have been divided into two groups: (1) those which radiate practically no energy at wavelengths below 2800 A and (2) those which do furnish energy below 2800 A. This classification omits all considerations of lamp dimensions, wattage, auxiliary equipment, and distribution of the radiation about the lamp. Nor does it take into consideration the visible or infrared radiation. In the first classification the most efficient lamp for the production of 2800–3200 A is the S-4 "capillary" type arc and for 3200–3800 A the BL fluorescent lamps. In the second classification the most efficient in the region below 2800 A is the low-pressure slimline lamp. The high-pressure, water-cooled A-H6 is most efficient in the 2800–3200 A region and also in the 3200–3800 A region.

Where total ultraviolet output rather than efficiency is the only consideration the relative ratings are as shown in Table 25. The lamps are again divided into two groups, those which do and those which do not emit radiation of shorter wavelength than 2800 A. The classification is on the basis of output only and omits all other considerations. The table shows that the most powerful source in any part of the ultraviolet

range is the 1000-watt H-6 water-cooled arc in quartz or in glass, depending upon whether the radiation below 2800 A is desired or not.

TABLE 25

Comparison of Lamps on Basis of Output *

Wavelength in Angstroms	Highest Output	Second	Third	Fourth
	Lamps emitting no energy below 2800 A			
2800–3200	H-6 in No. 774 glass	D-H1	S-1	S-4
3200–3800	H-6 in No. 774 glass	H-9	D-H1	E-H1
	Including lamps furnishing radiation below 2800 A			
0–2800	H-6 in quartz	Uviarc UA-3	Uviarc UA-2	Low-pressure slimline
2800–3200	H-6 in quartz	Uviarc UA-3	Uviarc UA-2	Low-pressure slimline
3200–3800	H-6 in quartz	UA32-A2	UA26-A2	Low-pressure slimline

* *Gen. Elec. Lamp Bulletin* LD-1.

Cyclic Variation of Light

The radiation from low-pressure lamps follows the variation in current through the tube very closely. Thus a lamp operated on 60-cycle alternating current emits radiation which falls almost to 0 each time the current passes through 0; that is, 120 times a second.

In high-pressure lamps the radiation is modulated at 120 cycles but does not actually fall to 0 when the current passes through 0. This is because at the high temperature of high-pressure arcs the heat capacity of the arc is sufficient to cause appreciable thermal excitation of the gas.

Low-Frequency Operation

When operated on alternating current an arc goes out at the end of each half cycle and must start again on the next half cycle. This can only occur if the electrodes remain hot and some ions remain in the space in the interval between half cycles. If the time interval becomes too long, the gas has time to deionize and the electrodes to cool, and the arc fails to start. Accordingly, 60-cycle lamps will not operate satisfactorily at frequencies lower than about 25 cycles.

Restarting of Arcs

If a high-pressure mercury arc is interrupted for long enough to allow the electrodes to cool and the gas to deionize, it will normally require several minutes after the reapplication of the voltage before the arc will strike again. This is because the starting voltage at the normal operating pressure is above the voltage available for operation. The lamp will not start again until the pressure has dropped to a value low enough for

the arc to start on the available voltage. This "restriking time" may vary from 3 to 8 min.

Zirconium Arc

A unique form of concentrated arc which approaches a point source has been developed by the Western Union Telegraph Company [9] for narrow-beam and high-intensity projection applications. Because of the high temperature at which it operates it radiates an appreciable quantity of ultraviolet. It consists of permanent fixed electrodes sealed into a glass bulb in an inert atmosphere. The cathode is a small tantalum (or other refractory metal) tube with a zirconium oxide core. The anode is a large metal disc concentric with the cathode. These are shown schematically in Fig. 25. The arc discharge heats the core at the end of the

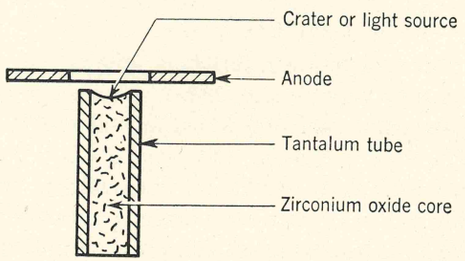


Fig. 25. Electrodes of zirconium concentrated arc.

cathode to a temperature in excess of 3000°K and, according to one view, forms a thin layer of metallic zirconium over it. A large part of the radiation comes from this surface. The remainder comes from the zirconium vapor and argon gas in the cathode-glow region close to the cathode. The diameter of the spot varies from 0.085 mm for the 2-watt lamp to 2.8 mm for the 300-watt lamp.

Figure 26*a* shows the spectral energy distribution for the 100-watt lamp enclosed in a glass bulb. The ordinates represent the energy radiated per unit area of the cathode spot over a portion of the spectrum 1 μ wide. The spectrum shows zirconium and argon lines as well as a continuum which extends to nearly 2000 A in the ultraviolet. The glass bulb limits the spectrum to wavelengths longer than 3000 A.

A similar 1000-watt arc has been developed for operation in the open air. Its spectrum accordingly is not limited by the glass and extends to about 2000 A, as is shown in Fig. 26*b*.

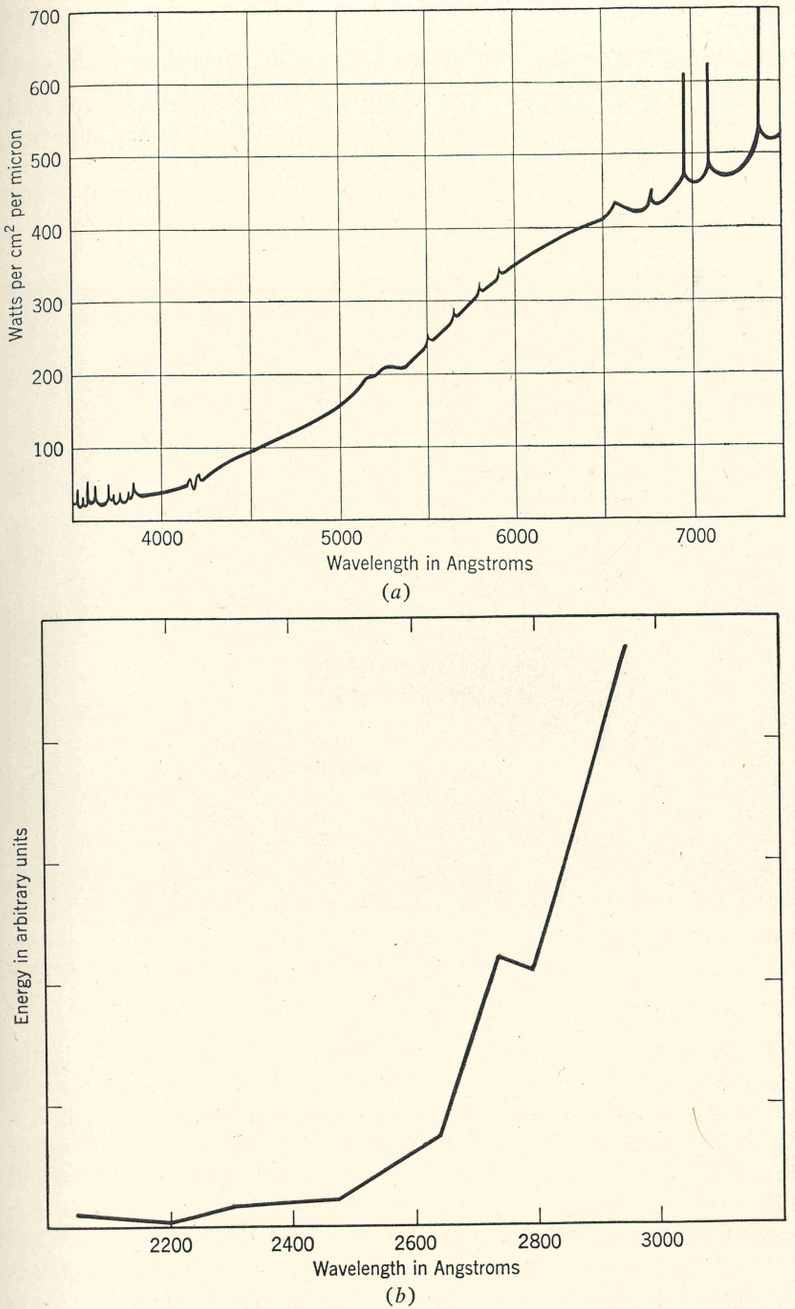


Fig. 26. Spectrum of zirconium arc. *a*. 100-watt arc in glass. *b*. 1000-watt Telco arc in air. (Courtesy of Western Union Telegraph Co.)

Hydrogen Arc

An arc in hydrogen has been found to give a strong continuous spectrum in the ultraviolet as far down as 1850 A. Various forms have been developed. Most of the earlier ones operated at high voltage. A low-voltage hydrogen lamp has been described by Smith and Fowler.[10] This is a d-c lamp with a separately excited hot cathode. At a pressure of

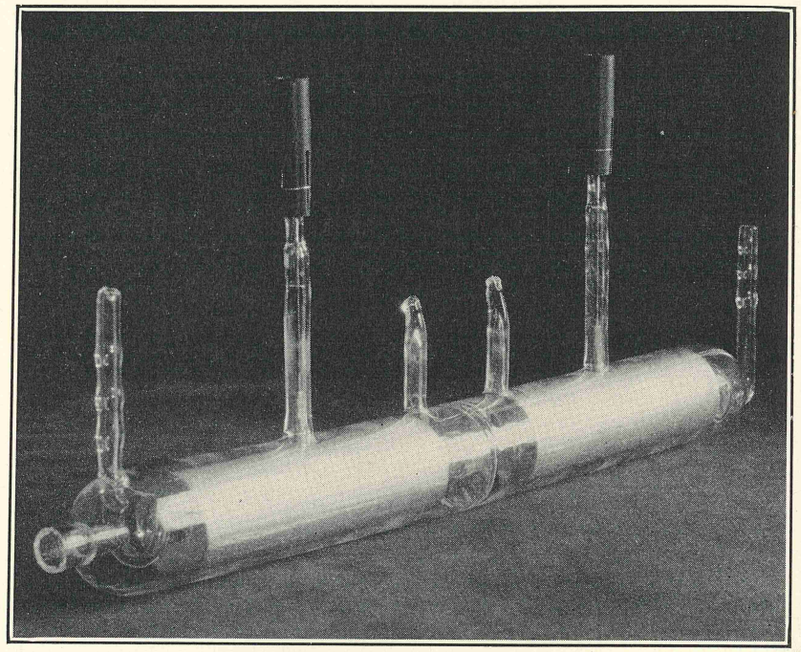
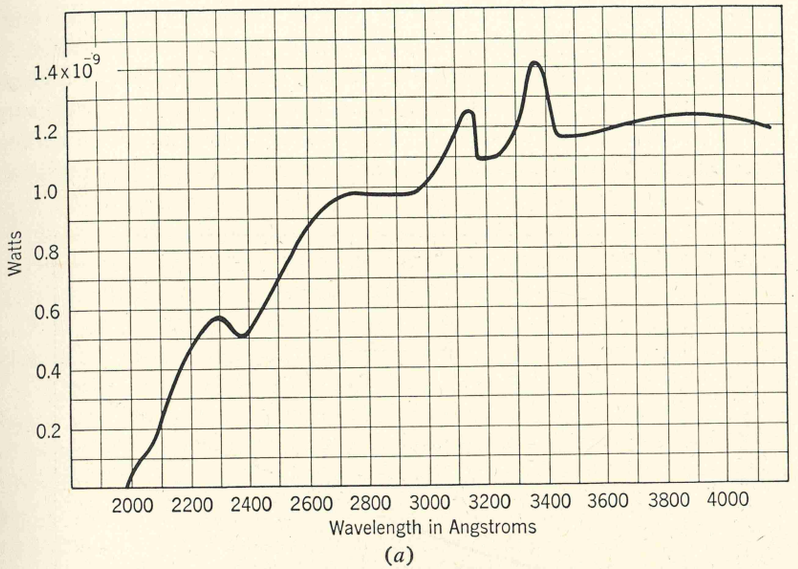


Fig. 27. Hydrogen arc in quartz. Emission is through windows at ends of tube. Vertical tubes at end are for water circulation. (Courtesy of Hanovia Chemical and Mfg. Co.)

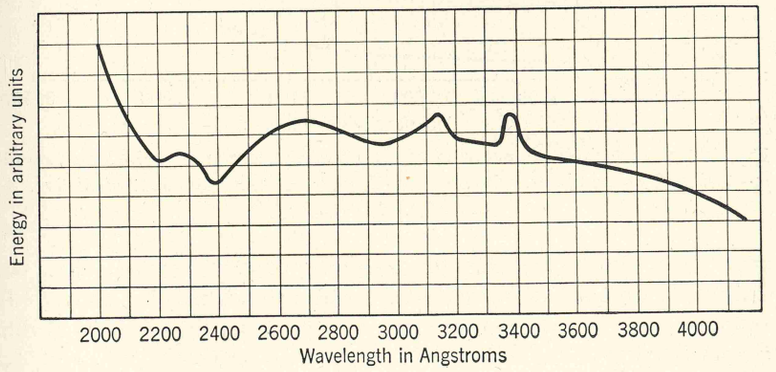
0.2 mm of hydrogen it operates on 220 volts with arc currents in the range from 0.5 amp to 20 amp. The discharge is viewed end on through an annular-shaped anode rather than laterally in order to obtain the greatest possible brightness. A commercial form of hydrogen arc is shown in Fig. 27. A high-intensity source which emits between 50 and 100 times as much radiation as comparable commercial sources has been described by N. A. Finkelstein.[11]

Figure 28*a* shows the energy from a hydrogen arc which is available at the exit slit of a monochromator as a function of wavelength. This is not the true energy distribution of a hydrogen arc but rather the avail-

able energy distribution when the arc is used with a particular instrument. The loss in the instrument due to the absorption of the quartz



(*a*)



(*b*)

Fig. 28. *a*. Energy from hydrogen arc available through monochromator. Arc operated at 3.4 amps, 70 volts direct current. (Courtesy of E. A. Taft and L. Apker.) *b*. Energy distribution in hydrogen-arc spectrum. (Calculated from Taft and Apker.)

prisms is considerable and is one of the chief factors responsible for the falling off of the curve toward the short wavelengths. If a correction is made for this loss as well as for the dispersion of the instrument, the true energy distribution of the arc is as shown in Fig. 28*b*.

High-Pressure Xenon Arc

A high-pressure 0.5 KW xenon arc operating at a pressure of about 20 atmospheres has been found to be a very intense source of continuous ultraviolet radiation.[12] In the wavelength range 2200–3400 A, its spectral energy distribution is very closely matched by that of a black body at a temperature of 6600°K. Over this range its intensity is from two to five times as great as that for the corresponding area of a carbon arc. Figure 29 shows a comparison of the intensity of the radiation

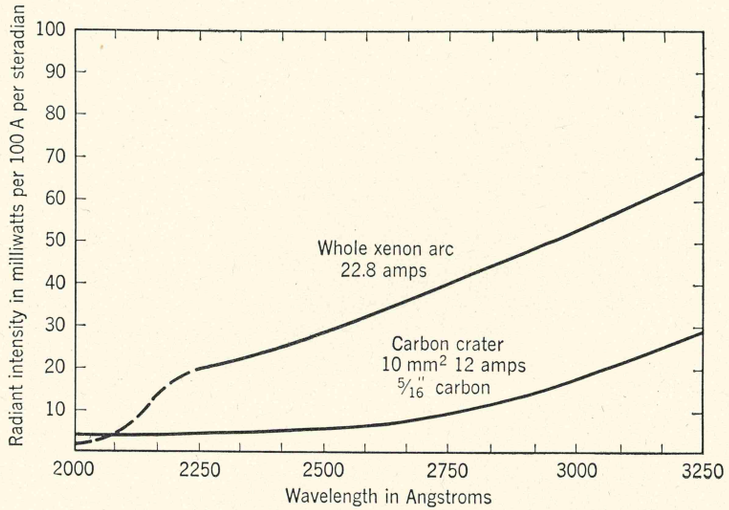


Fig. 29. Comparison of spectrum of high-pressure xenon arc with corresponding area of carbon-arc crater. (W. A. Baum and L. Dunkelman, *J. Optical Soc. Am.*, **40**, 782, 1950.)

from these two sources in milliwatts per steradian over a 100–A wave band as a function of wavelength. These values may be converted to milliwatts per square centimeter at 1 meter from the lamp by dividing by 10,000.

If the most intense part of the xenon arc is compared with an equal area of a carbon arc, the difference becomes even more marked. For example, at 2500 A the radiance in milliwatts per 100-A band per steradian per square centimeter of the most intense part of the xenon arc exceeds that of a Hanovia hydrogen arc by a factor of more than 10, and the carbon crater by more than 20. The xenon lamp is more intense in the ultraviolet than the H-4 (with glass envelope removed) and less intense over most of the range than the H-6.

Carbon Arcs

The carbon arc is a typical example of an open arc. It consists of a discharge between two carbon electrodes in air at atmospheric pressure. The electrodes are carbon rods about ½ in. in diameter (more or less depending upon the type of arc) and several inches long. Like most arcs it has a negative volt ampere characteristic and hence must be operated in series with a suitable ballast.

The arc is started by bringing the two electrodes into contact and then separating them slightly. The resulting discharge is intensely bright and hot.

During operation the electrodes are consumed. The positive electrode is burned at the rate of about 2 in. per hour in low-intensity arcs and as much as 12 in. per hour in high-intensity arcs. The negative electrode is consumed at a somewhat lower rate. In order to maintain the constancy of the arc, the electrode must be fed either by hand or by an automatic device in order to maintain a constant arc gap.

When operated on direct current, an intensely hot, crater-shaped depression is formed on the positive electrode. This crater is responsible for about 90 per cent of the luminosity in low-intensity arcs. On alternating current the luminosity is divided between the two electrodes. The size of the crater increases with arc current according to the equation

$$A = 7 + 0.47I^e \text{ sq mm}$$

where $e = 1.35$–1.4.
I = arc current in amperes.

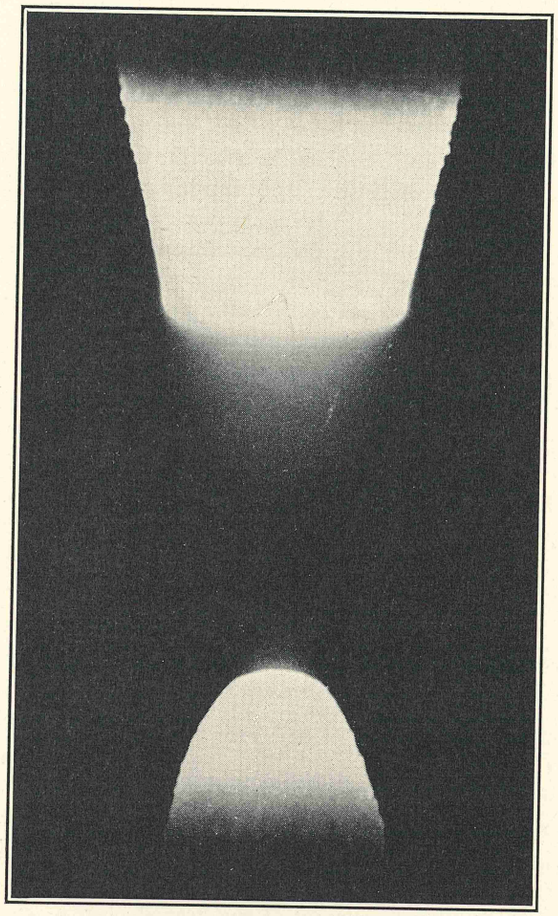
The temperature of the carbon-arc positive crater has been determined by Chaney to be nearly 4000°K, and Suits [13] has found the temperature of the arc stream itself to be 5500°K.

In order to insure the centering of the crater on the anode and its stability, the carbon electrode is made hollow and the core is filled with a softer grade of carbon.

The positive-ion bombardment of the cathode forms an intensely hot spot on it. This spot which furnishes the thermionic emission to maintain the arc is called the cathode spot. Figure 30*a* shows a low-intensity d-c carbon arc.

With a solid or neutral core the radiation is almost entirely from the positive crater. By introducing flame-supporting minerals into the core of the carbon the source of the luminosity is greatly increased and is largely transferred from the crater to the flamelike arc stream as is shown in Fig. 30*b*. This makes the "flaming arc" a very versatile source

of radiation. Certain salts added to the core improve the steadiness of the arc as well as alter its brightness. In flaming arcs as much as 70–90



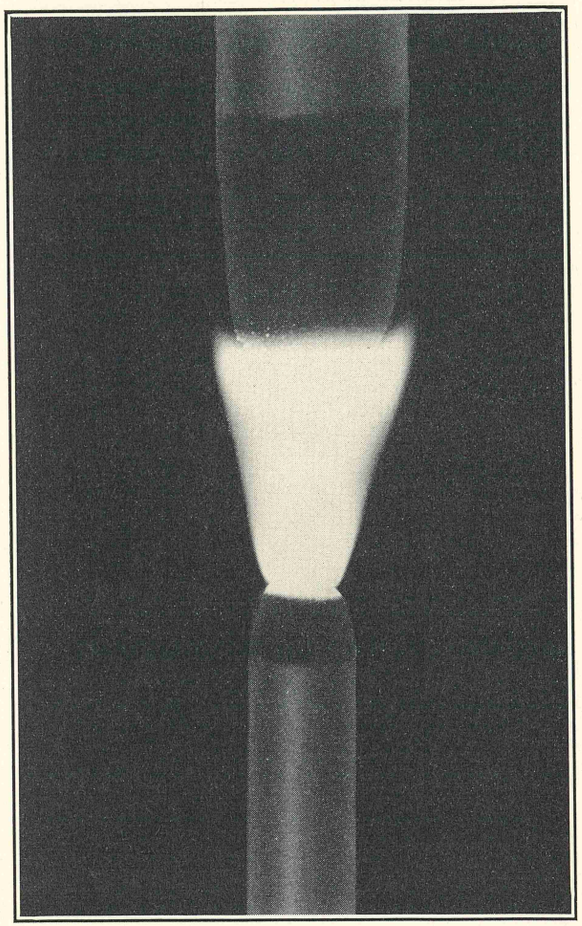
(*a*)

FIG. 30. Various types of carbon arcs. *a*. Low-intensity d-c carbon arc. *b*. Flame-type carbon arc. *c*. High-intensity d-c carbon arc with rotating positive carbon. (Courtesy of National Carbon Co.)

per cent of the radiation may be emitted by the vapor which may have a temperature between 6000 and 8000°K.

At higher current densities in the range of 62 to 186 amp per cm^2 the anode spot spreads over the entire tip of the carbon, resulting in

rapid evaporation of the flame material. This produces a brilliant stream of luminous vapor called the anode or tail flame in front of the



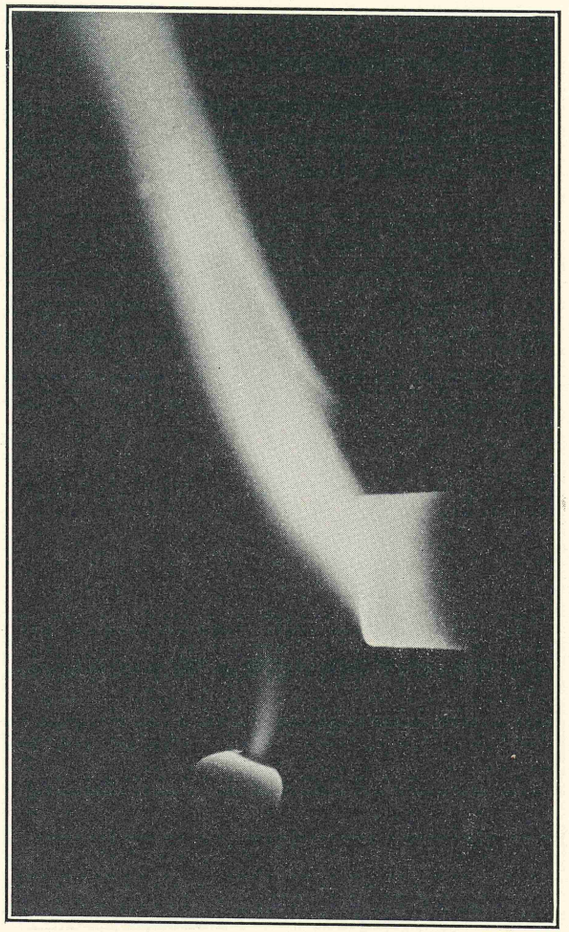
(*b*)

FIG. 30 (*Continued*).

anode as shown in Fig. 30*c*. This type of arc is variously called the high-current, high-intensity, or Beck arc.[14] It is used in searchlights and other projectors. In this type of arc brilliancies as high as 200,000 candles per cm^2 have been produced.

The spectrum of the carbon arc consists of the continuous spectrum

of the incandescent electrodes on which is superimposed the band spectrum of the luminous gas. The resulting spectrum is relatively con-



(*c*)

FIG. 30 (*Continued*).

tinuous. The cyanogen bands between 3800 and 3900 A are a particularly marked feature of this spectrum and add a pronounced peak in this region. This peak is very noticeable in Figs. 31–39.

The output of radiation from a carbon arc increases with increase in arc current. Over most of the spectrum the increase is approximately

proportional to the current. In the ultraviolet, however, in the region around 4000 A the intensity increases more rapidly than the current. In this region doubling the current may increase the intensity 2½- to 5-fold.

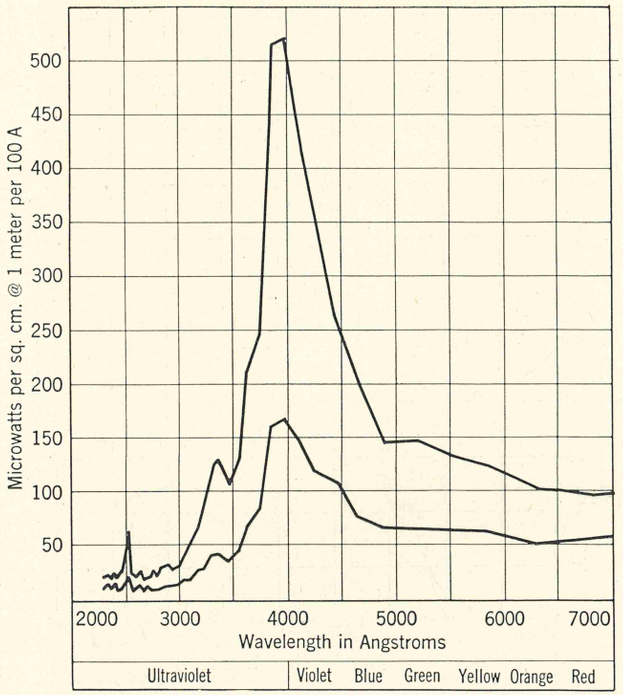


FIG. 31. Spectral energy distribution of carbon arc with cerium-cored carbons (National Sunshine). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog,* Section A-4300.)

The energy distribution curves for a number of kinds of arc carbons are shown in Figs. 31–39. They give the intensity in microwatts per square centimeter falling on a surface at a distance of 1 meter from the arc. The intensity at any other distance may be calculated by assuming that the intensity varies inversely as the square of the distance. The data refer to bare arcs without reflectors. Reflectors increase the intensity from 2- to 5-fold, depending upon their design and material.

Figure 31 shows the energy distribution for "Sunshine" carbons at 60 and 30 amp alternating current, respectively. The core of these car-

bons contains cerium. As can be seen from the figure the arc radiates considerable energy in the ultraviolet region below 3000 A. The large increase in output with increasing current in the region around 4000 A is very noticeable.

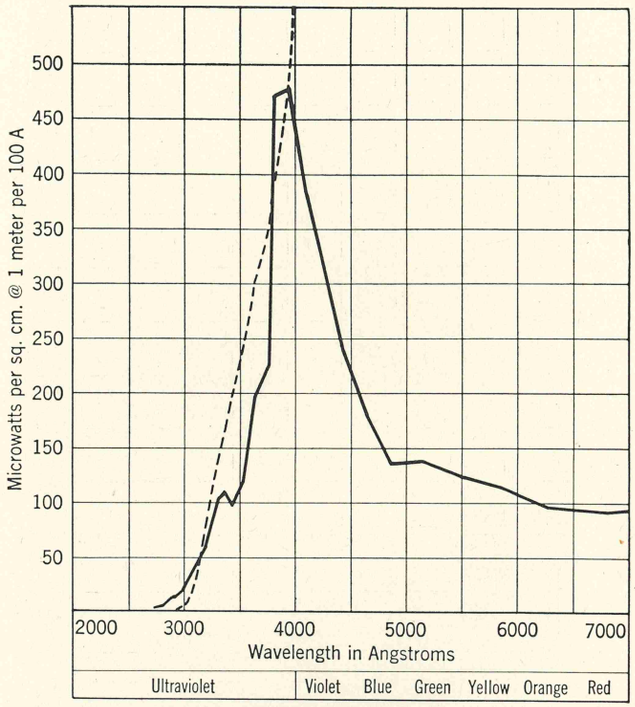


FIG. 32. National Sunshine Carbon with Corex filter compared with natural sunlight. Solid line, with Corex D filter. Dotted line, natural sunlight. (*National Carbon Co. Catalog,* Section A-4300.)

For sunlamp purposes the region below 3000 A is filtered out by means of a Corex D filter which has relatively little effect on the longer wavelength energy. In the region between 3000 and 4000 A the Sunshine carbon arc operating at 60 amps alternating current when used with a Corex D filter at a distance of 1 meter is a fair approximation to natural sunlight, as is shown in Fig. 32. At longer wavelengths, however, the solar radiation is far more intense. At 7000 A the intensity of the solar radiation is about ten times that of the arc.

Figure 33 shows the spectral energy distribution of National B carbons with a core containing iron. This spectrum has many lines from the visible through the ultraviolet to 2300 A. Its ultraviolet output is considerably higher than for the Sunshine carbons, although its visible

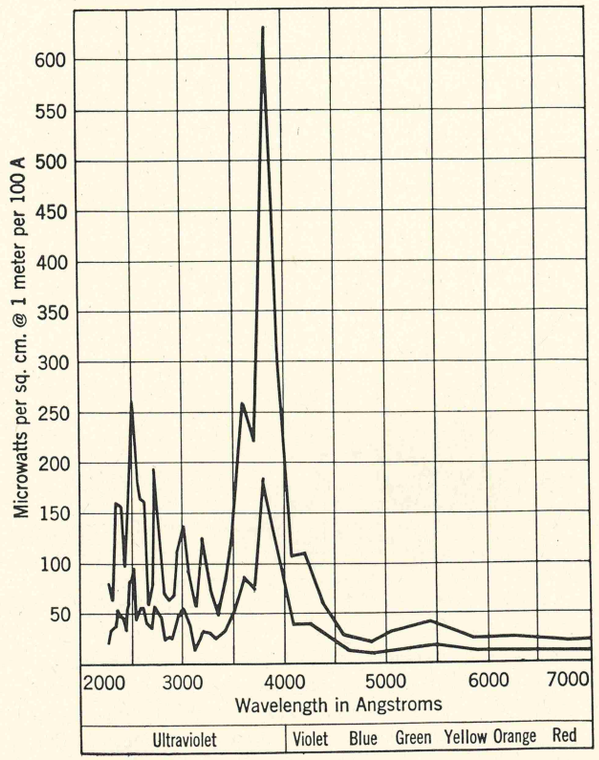


FIG. 33. Spectral energy distribution of carbon arc with iron-cored carbons (National B). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog,* Section A-4300.)

and infrared output are considerably less. The difference in spectral response near the short-wave cut-off should not be overlooked. The arc radiates a significant amount of radiation at wavelengths less than 3000 A. It is just in this region that the erythema curve shows a very pronounced maximum.

Figure 34 shows the spectral energy distribution of an arc with C carbons which contain iron, nickel, aluminum, and silicon in the core. Its total ultraviolet intensity is somewhat higher than for the B carbons, and it is significantly higher in the 2800–3200 A region.

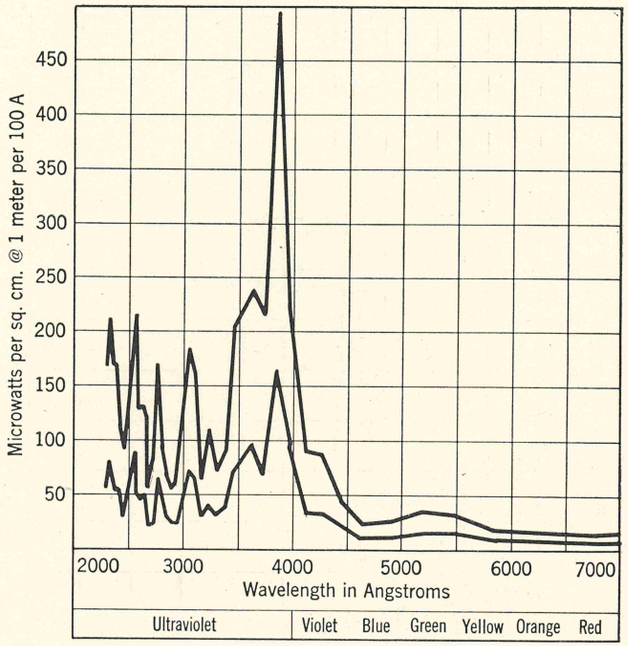


FIG. 34. Spectral energy distribution of carbon arc with carbons containing iron, nickel, aluminum, and silicon in the core (National C). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. *National Carbon Co. Catalog,* Section A-4300.)

Figure 35 shows the spectral energy distribution of an arc with D carbons. These have a core of soft carbon which improves the steadiness of the arc. Otherwise it does not differ essentially from solid-carbon electrodes. Its ultraviolet output is relatively low except for the strong cyanogen bands around 3800 A.

Figure 36 shows the spectral energy distribution of the arc with E carbons which contain strontium in the core. This spectrum is relatively weak in the ultraviolet but strong in the red and infrared.

Figure 37 shows the spectral energy distribution of the arc with K carbons which are cored with cobalt. This arc produces strong bands

in the ultraviolet at 2400 and 3500 A. This carbon has a higher emission in the ultraviolet below 2500 A than any of the other carbons.

Figure 38 shows the spectral energy distribution of the arc with U carbons which have a polymetallic core producing a very strong ultra-

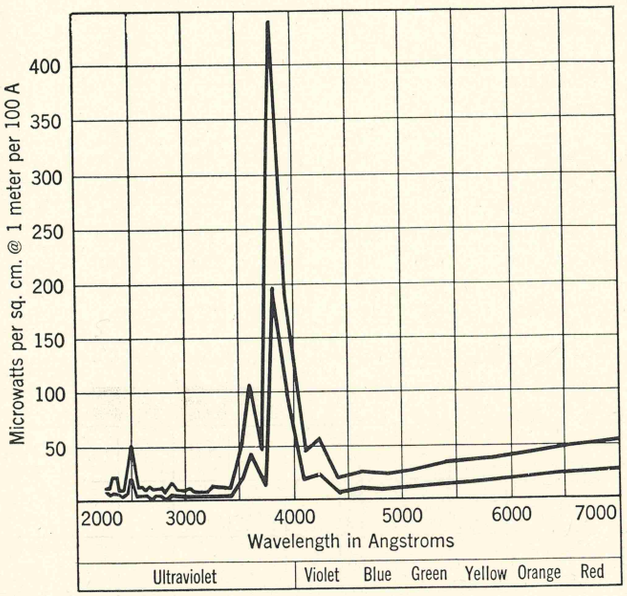


FIG. 35. Spectral energy distribution of carbon arc with core of soft carbon (National D). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog,* Section A-4300.)

violet emission. Between 2600 and 2900 A its emission is about 1¾ times that of the C carbon.

Figure 39 shows the spectral energy distribution of the arc with W carbons. These are similar to the U carbons, but they are designed for use at high arc currents for applications such as commercial production of vitamin D.

Table 26 shows the intensity of the radiation in various wavelength bands falling on a unit area at a distance of 1 meter from the different types of bare carbon arcs shown in Figs. 31–39. These wavelength bands have been chosen so that comparisons may be made with the mercury arcs in Tables 6 to 25.

From Table 26 it is evident that carbon arcs are very intense though

TABLE 26

INTENSITY OF RADIATION FROM BARE CARBON ARCS WITHOUT REFLECTORS IN MICROWATTS PER SQUARE CENTIMETER AT DISTANCE OF 1 METER FROM ARC *

Type of Arc	Current	Volts	2300–2800 A	2800–3200 A	3200–3800 A	2300–3800 A	3800–7000 A
"National" Sunshine carbon	60	50	129	187	1010	1326	6094
"National" Sunshine carbon with Corex D filter	60	50	2	103	860	965	5445
"National" B carbon	60	50	684	326	1010	2020	1910
"National" C carbon	60	50	613	413	1188	2214	1656
"National" D carbon	60	50	80	40	296	416	1819
"National" E carbon	60	50	221	130	584	935	5665
"National" K carbon	60	50	709	262	1310	2281	1529
"National" U carbon	60	50	746	589	1000	2335	2148
"National" W carbon	80	60	1970	1627	2620	6217	6223

* Calculated from *National Carbon Co. Catalog*, Section A-4300.

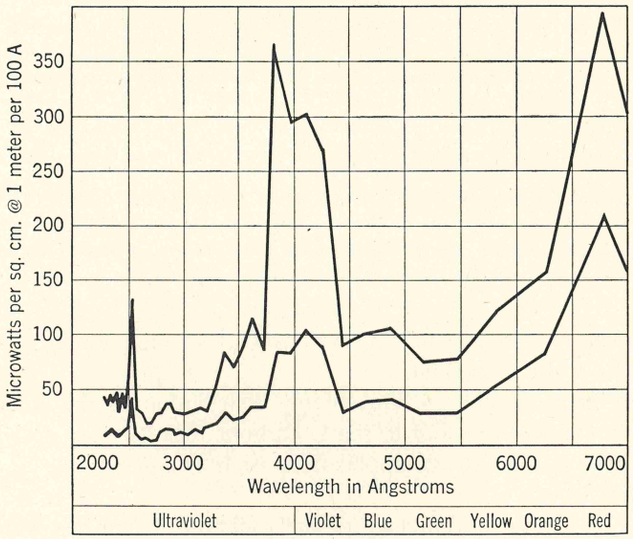


FIG. 36. Spectral energy distribution of carbon arc with strontium-cored carbons (National E). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog*, Section A-4300.)

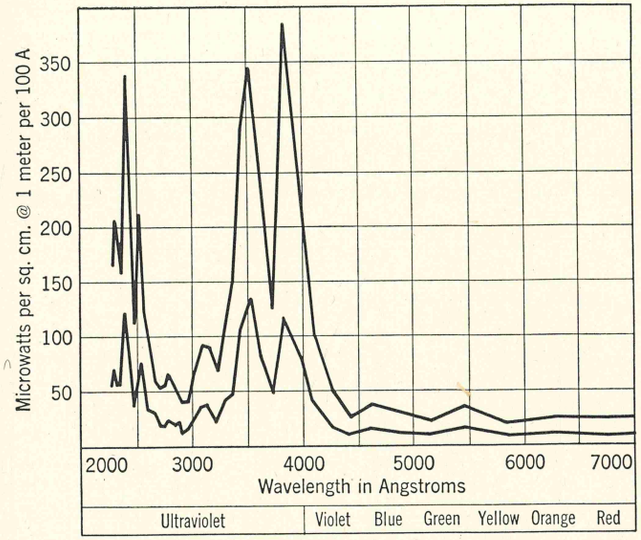


FIG. 37. Spectral energy distribution of carbon arc with cobalt-cored carbons (National K). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog*, Section A-4300.)

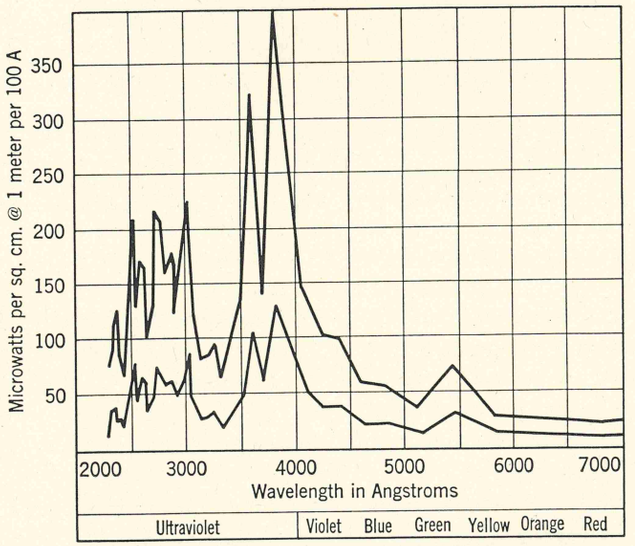


FIG. 38. Spectral energy distribution of carbon arc with polymetallic-cored carbons (National U). Upper curve, 60 amperes alternating current, 50 volts across arc. Lower curve, 30 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog*, Section A-4300.)

not necessarily efficient sources of ultraviolet. Their usefulness lies in the fact that they are such extremely concentrated sources. That is, a larger amount of radiation is obtained from a smaller area of radiating surface than is the case with any of the enclosed arcs. On the other hand, if efficiency is a consideration, the carbon arcs are less efficient

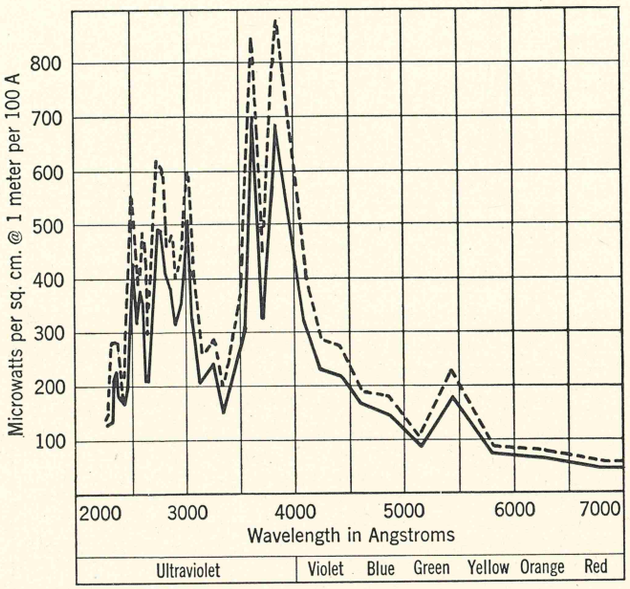


FIG. 39. Spectral energy distribution of carbon arc with polymetallic-cored carbons for high currents (National W). Upper curve, 80 amperes alternating current, 60 volts across arc. Lower curve, 80 amperes alternating current, 50 volts across arc. (*National Carbon Co. Catalog,* Section A-4300.)

in many cases than mercury arcs. For example, the intensity of radiation between 2300 and 2800 A at 1 meter from a national W carbon arc is 1970 μw per cm^2. Since the input to the arc is 4800 watts this is 0.41 μw per cm^2 per watt input. The intensity in the same wavelength region at the same distance from a 30-watt germicidal lamp is 75 μw per cm^2 or 2.5 μw per cm^2 per watt input.

In general, the advantage lies with the carbon arc if a high intensity is required from a single unit. On the other hand, when efficiency is a consideration the advantage usually lies with the mercury arc.

The relatively short life of a carbon arc, namely, a few hours before the carbons must be replaced, is a disadvantage in comparison with the

life of an enclosed arc, namely, several thousand hours. In some applications the presence of the combustion products of the arc is also a disadvantage.

Table 27 shows the relative energy output of different types of carbons in various bands of the spectrum in terms of the Sunshine carbon which is taken as 100 per cent in each case. It is intended only for comparison of the various carbons with each other.

TABLE 27

COMPARISON OF VARIOUS TYPES OF ARC CARBONS *

	1700–3100 A, Per Cent	3100–6300 A, Per Cent	6300–11,250 A, Per Cent	11,250–120,000 A, Per Cent
Sunshine Carbon 60A 50V AC	100	100	100	100
B Carbon 60A 50V AC	420	48	60	126
C Carbon 60A 50V AC	477	44	39	97
D Carbon 60A 50V AC	54	28	69	128
E Carbon 60A 50V AC	146	69	120	105
K Carbon 60A 50V AC	430	46	53	120
U Carbon 60A 50V AC	520	50	44	98
W Carbon 80A 50V AC	1110	116	84	148

The choice of these bands is arbitrary and is based on the penetration of the radiation. Thus the characteristics of these bands may be described as follows:

1700–3100 A, ultraviolet fully absorbed by ordinary glass.
3100–6300 A, nonpenetrating ultraviolet and visible.
6300–11,250 A, penetrating visible and infrared.
11,250–120,000 A, nonpenetrating heat.

* *National Carbon Co. Catalog,* Section A-4300.

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3 Incandescent Sources of Radiation

Introduction

In comparison with arcs, terrestrial incandescent bodies are relatively weak and inefficient sources of ultraviolet. An incandescent body is defined as one whose radiation is due to its temperature. A characteristic feature of this kind of radiation is its broad continuous spectrum. The ultraviolet portion of this spectrum is only a small part of the whole and is very largely long-wave ultraviolet. Accordingly, incandescent sources radiate very little ultraviolet, and what they do radiate is accompanied by a large amount of visible and infrared radiation. Thus they are not only weak but also inefficient ultraviolet generators.

The total amount of energy and the distribution of energy in the spectrum of an incandescent body are chiefly functions of temperature and depend upon the chemical nature of the radiator only to a lesser extent. In gas discharges or arcs, on the other hand, the nature of the gas determines the character of the spectrum. The difference between a discharge in mercury vapor and one in neon is evident at a glance, whereas the difference between, say, incandescent tungsten and tantalum at the same temperature can be detected only by means of careful measurements. The most convenient form of incandescent radiator is of course the ordinary incandescent lamp.*

Total Radiation

The laws of radiation from incandescent bodies have been studied both theoretically and experimentally, and the energy emitted can be calculated with a high degree of accuracy. The total amount of energy

* As has been pointed out on page 19, Chapter 2, the electrodes in some arcs are heated to incandescence so that the spectra of these arcs are a mixture of the continuous and the line type.

radiated by a hot body is proportional to the fourth power of its absolute temperature. This relation, known as the Stefan-Boltzmann law is given by the equation

$$W = \sigma T^4 \tag{1}$$

where W = watts radiated by a square centimeter of the radiating surface.
T = absolute temperature.
$\sigma = 5.672 \times 10^{-12}$ watt·cm^{-2}·deg^{-4} for an ideal or black body radiator.

The rigorous form of this equation is $W = \sigma\ (T^4 - T_0^4)$ where T_0 is the ambient temperature. If T is greater than $4T_0$ the error introduced by neglecting T_0 is less than 0.5 per cent, so that the above form can be used for practically all cases of incandescence.

From this relation it can be seen that the total amount of energy radiated by an incandescent body increases extremely rapidly with the temperature. A few numerical values are given in Table 1.

TABLE 1

Total Energy Radiated per Unit Area of Radiating Surface by a Black Body at Various Temperatures

T, °K	Watts/cm^2
1000	5.74
1500	29
2000	92
2500	224
3000	464

These values are the total amount of energy radiated by a unit area of surface at various temperatures. The amount of energy radiated *normal* to the surface (in the case of a flat surface) is obtained by dividing the values given by equation 1 and Table 1 by π.

Distribution of Energy

The Stefan-Boltzmann law gives the total amount of energy radiated by a black body, but it does not give any information about the distribution of this energy in the spectrum. This is given by Planck's distribution law. In deriving this law, which gave the first satisfactory agreement between theory and experiment, Planck suggested the quantum nature of radiant energy and laid the foundation for the quantum theory.

Planck's distribution law for an ideal radiator (or black body) is:

$$E_\lambda \, d\lambda = \frac{3.7403 \times 10^{-12}\lambda^{-5}}{e^{1.4384/\lambda T} - 1} \text{ watts per cm}^2 \text{ per 100 A band of spectrum}$$

where λ = wavelength in centimeters.
T = temperature in degrees K.
E_λ = rate in watts at which energy is radiated per 100 A wavelength band from 1 sq cm of radiating surface at the wavelength λ.

Figure 1 shows a plot of this equation for a perfect or ideal radiator (called a black body) at 3000°K. The abscissae represent wavelengths, and the ordinates give the rate of radiation at the corresponding wavelengths. The area under the curve gives the total energy radiated. The curve shows that the intensity of the radiation is not uniform throughout the spectrum but increases rapidly in passing from short to longer wavelengths. It passes through a maximum at about 1 μ (10,000 A) and then falls gradually. This type of curve is typical qualitatively of all incandescent bodies. The shaded portion of Fig. 1 represents the energy within the limits of the visible spectrum and the cross hatched portion the energy in the ultraviolet. Only 8 per cent of the energy radiated lies in the visible, and about 0.2 per cent is in the ultraviolet. The remainder is in the infrared.

Figure 2 shows a family of energy distribution curves calculated by Planck's distribution law for temperatures of 1000, 1600, 2000, 3000, 4000, and 5000°K. The general shape remains the same as the temperature is increased, but the total area under the curves (which is proportional to the total energy radiated) increases with temperature in accordance with the Stefan-Boltzmann fourth power law. The ordinates increase, and the maximum in the curve shifts towards shorter wavelengths with increasing temperature. This accounts for the common observation that with increase in temperature the light from an incandescent body changes from red to white (i.e., from red hot to white hot). Thus as the temperature is increased the fraction of the total area under the curve which falls within the limits of the visible spectrum increases. Likewise the fraction of the total energy falling in the ultraviolet portion of the spectrum increases. Not only does the fraction of the energy falling within these limits increase, but the actual *amount* also increases. From the general trend of the curves it is evident that in order to obtain large amounts of ultraviolet by this method temperatures far in excess of any so far attained (except in nuclear explosions) would

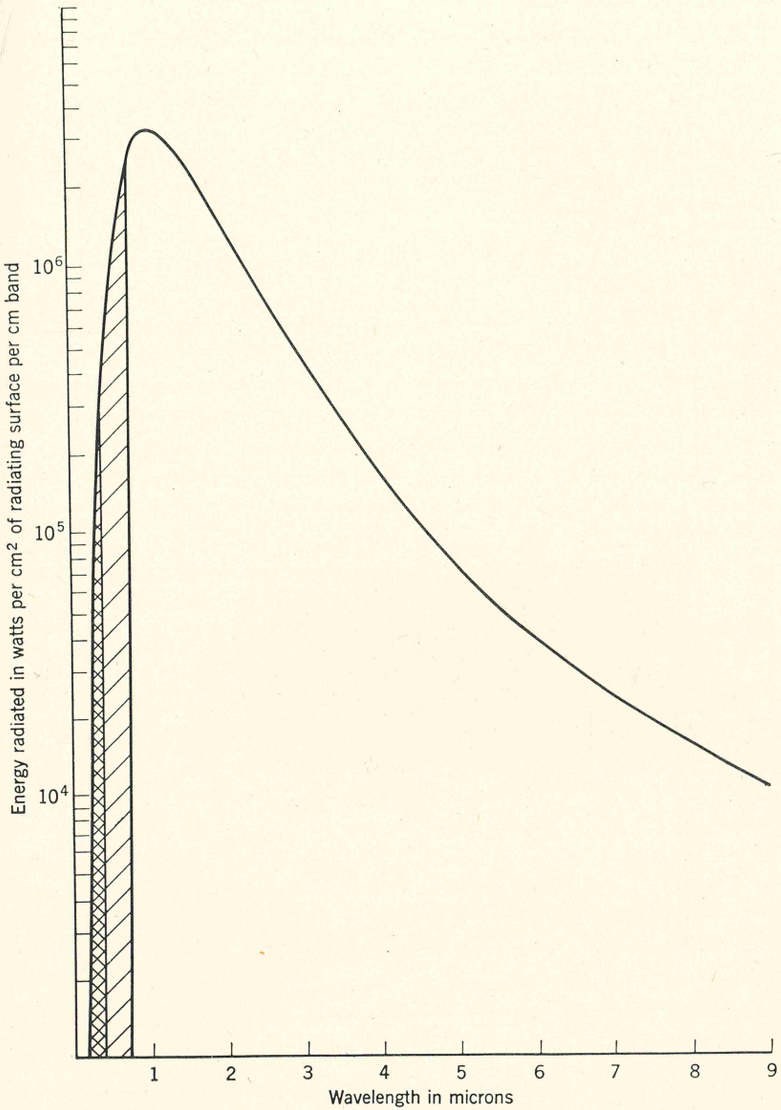

FIG. 1. Planck's distribution law for a black-body radiator at 3000°K. Shaded area, visible radiation; cross-hatched area, ultraviolet radiation.

be required. The chief limitation in attaining higher temperatures is the lack of materials which will withstand these temperatures.

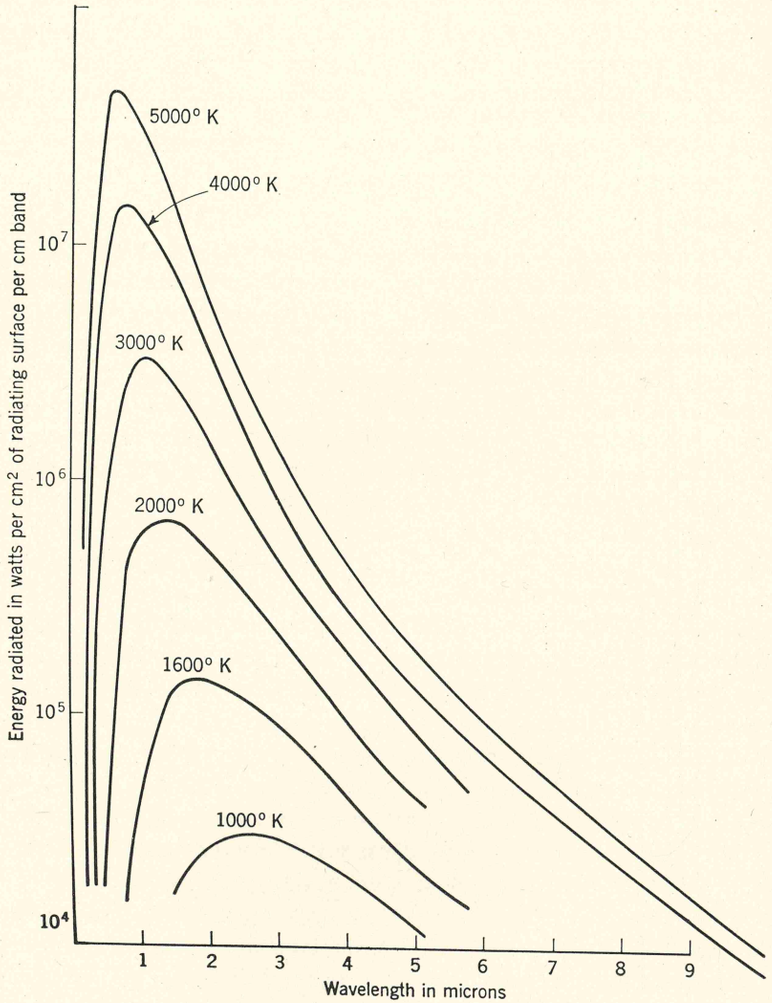

FIG. 2. Energy distribution for a black body at various temperatures.

ULTRAVIOLET ENERGY RADIATION

The per cent of the total energy which is radiated in the ultraviolet at any temperature can be shown more conveniently by the set of curves shown in Fig. 3. These curves have been derived from data calculated

by Holladay.[1] Each curve shows the per cent of the total energy radiated by a black body * which falls between the wavelength 0 and the wavelength λ, at any given temperature. Thus the ordinates of these curves at the wavelength 4000 A give the per cent of the total amount of energy radiated by a black body between the wavelengths 0 and 4000 A, i.e., in the ultraviolet. At 3000°K about 0.2 per cent of the

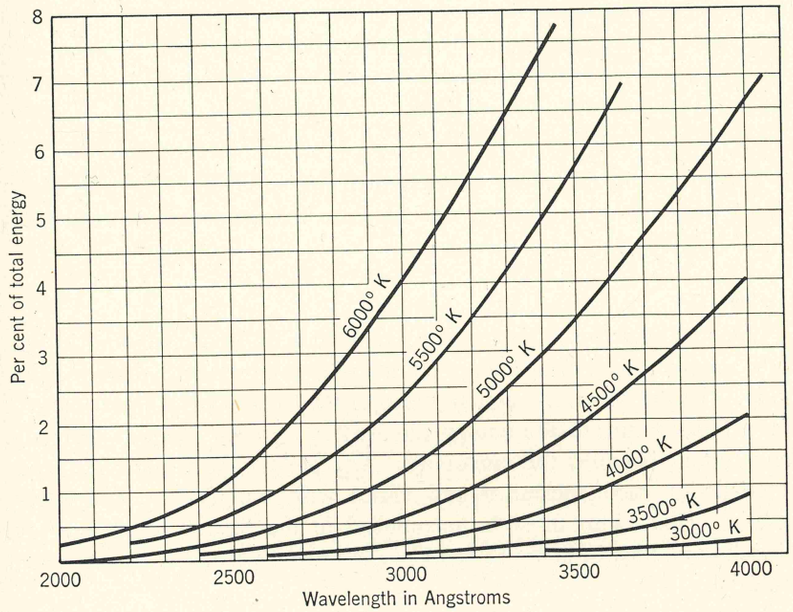

FIG. 3. Per cent of total energy radiated by a black body between wavelength 0 and wavelength λ. (L. L. Holladay, *J. Optical Soc. Am.*, **17**, 329, 1928.)

total energy radiated by a black body lies at wavelengths shorter than 4000 A. At 4000°K it has increased to 2 per cent and at 5000°K to 6.6 per cent. Not only does the *fraction* of the energy increase with increasing temperature, but the *amount* of energy also increases because of the increase of total energy radiated in accordance with the fourth power law. This is shown in Table 2 which gives the fraction of the total energy radiated in the ultraviolet as well as the absolute value for several different temperatures.

* For nonblack bodies the values must be multiplied by a factor G which is the ratio of the lumens per watt for the surface concerned to the lumens per watt for a black body at the same color temperature. For tungsten $G = 1.25$ may be used as a first approximation.

TABLE 2

ENERGY RADIATED BY A BLACK BODY (OR IDEAL RADIATOR) IN THE ULTRAVIOLET

Temperature	Energy Radiated between 0 and 4000 A	
	Per Cent	Watts per cm^2
2000	0.0017	0.0015
2600	0.0522	0.13
3000	0.219	1.00
3500	0.797	6.81
4000	2.009	29
5000	6.6	234
6000	14.16	1040
8000	32.00	7370

The energy in the short wavelengths, that is, in the blue and ultraviolet, increases very rapidly with increase in wavelength as is evident from the steep slopes of these curves.

EMISSIVITY

Practical radiators differ from black bodies or ideal radiators in that they always radiate less energy at any given wavelength than a black body. The ratio of the actual energy radiated by any substance at a given temperature to the energy radiated by a black body at the same temperature is called the emissivity. The emissivity is a specific characteristic of each substance and varies with temperature and wavelength. This factor must be introduced in the Stefan-Boltzmann and Planck equations in order to calculate the energy radiated by any given material.

The ratio of the *total* amount of energy radiated by any substance to the total amount of energy radiated by a black body is called the total emissivity. Some values of total emissivity for materials commonly used in lamps and electron tubes are given in Table 3.

TABLE 3

TOTAL EMISSIVITY e_t FOR VARIOUS METALS

Metal	Total Emissivity e_t at	
	1000°C	2000°C
Tungsten	0.15	0.28
Molybdenum	0.13	0.24
Platinum	0.15	....
Tantalum		0.26
Nickel	0.19	
Columbium		0.24

Thus the radiation from a tungsten surface at 2000°K would be 0.28 times the amount for a black body at the same temperature. From Table 1 a black body radiates 92 watts per cm^2 at 2000°K. Accordingly, at this same temperature tungsten would radiate 0.28 $\times$ 92 or 24 watts per cm^2.

The emissivity must also be introduced in Planck's equation. For any given material the value of $E_\lambda\, d\lambda$ in the Planck equation must be multiplied by the appropriate value of spectral emissivity. This spectral emissivity is a function of temperature as well as wavelength. Some values of spectral emissivity for tungsten at different temperatures are shown in Table 4. Thus it can be seen that the values of $E_\lambda\, d\lambda$ calculated by Planck's equation must be multiplied by a factor of about 0.40 for tungsten.

TABLE 4

SPECTRAL EMISSIVITY FOR TUNGSTEN *

Temperature, °K	Spectral Emissivity at				
	λ = 6650 A	λ = 4670 A	λ = 4000 A	λ = 3000 A	λ = 2600 A
2000	0.435	0.469			
2500	0.425	0.462			
3000	0.415	0.455			
3500	0.405	0.449			
3655	0.402	0.447			
2900	.....	.....	0.45 †	0.42 †	0.40 †

* From W. E. Forsythe, and A. G. Worthing, *Astrophys. J.*, **61**, 146 (1925).
† From F. Hoffman and H. Willenberg, *Physik. Z.*, **35**, 713 (1934).

FUNDAMENTALS OF INCANDESCENT LAMPS

From the foregoing discussion it is evident that, in order to obtain a high output of ultraviolet from an incandescent body, a high temperature is required. Tungsten and carbon, two highly refractory materials, have been used for this purpose since the melting point of tungsten is 3655°K and that of carbon about 3868°K. The most convenient device for making use of the radiation from incandescent bodies is the ordinary incandescent lamp. Tungsten has proved to be the most satisfactory material for lamp filaments.

The ordinary tungsten filament lamp consists of a coiled filament of fine tungsten wire mounted in a glass bulb which is either highly evacuated or filled with an inert gas. The filaments are of a wide variety of sizes and shapes, depending upon the use to which the lamp is to be put, but in general they are closely wound coils. By using a coiled form

of filament instead of a straight wire, the conduction and convection losses to the gas are reduced and lamp efficiency is increased. In many lamps the filament is a coiled coil, that is, the coil itself is coiled. The radiation from the filament may be calculated from a knowledge of the area of the filament, its temperature, and the wattage input.

The efficiency of lamps is usually expressed in terms of the quantity of light flux or lumens per watt input to the lamp. This increases rapidly with increase in filament temperature. For instance, the efficiency of a tungsten surface at 2400°K is 9.37 lpw, whereas at 2500°K it is 11.67 lpw. The ultraviolet output likewise increases with increase in temperature.

In order to get the maximum output it is necessary to operate the filament at the highest possible temperature. The limiting factor in obtaining a high filament temperature is not the melting point of the filament but its vapor pressure. Vaporization of the filament material eventually leads to burn-out when enough tungsten has evaporated to reduce the filament weight by approximately 5 per cent (in the case of gas-filled lamps). The metal which vaporizes from the filament condenses as a dark deposit on the bulb wall, reduces the transmission of the bulb for radiation, and so progressively decreases the efficiency of the lamp during its life. The rate of vaporization and also blackening of the bulbs is reduced to a considerable extent by filling the bulb with an inert gas. Argon or mixtures of argon and nitrogen are most commonly used. Tungsten filament lamps operate at filament temperatures of from 2400 to 3450°K, depending upon life and efficiency requirements. The lower temperature is used for ordinary vacuum lamps which have a life of 1000 hr, and the higher temperature is used for photoflood lamps which have a life of only a few hours. Most of the standard gas-filled lamps operate at temperatures in the range between 2700 and 3050°K.

From 68 to 88 per cent of the wattage input to an incandescent lamp filament is radiated by the filament in the form of ultraviolet, visible, or infrared radiation and is transmitted by the bulb. The remainder of the energy is absorbed by the bulb and base and is partly carried away by conduction and convection and partly reradiated as long-wave infrared. In gas-filled lamps 5 to 25 per cent of the energy from the filament is carried to the bulb by the conduction and convection through the gas. However, this loss is more than offset by the gain in efficiency due to operating the filament at a higher temperature which the gas makes possible.

Output of Radiation from Various Types of Lamps

Table 5 shows the energy radiated in various regions of the ultraviolet and visible spectrum by a number of standard incandescent lamps as well as by several lamps designed for special purposes. No energy is shown for wavelengths shorter than 2800 A, because these wavelengths are not transmitted by ordinary lamp bulbs. The amount of energy radiated by the filament in this region is so small that there would be very little advantage in using bulbs of quartz or ultraviolet-transmitting glass. For example, a perfect radiator at 3000°K radiates 0.2 per cent of its energy in the ultraviolet and only a few one-hundredths of a per cent of this is at wavelengths shorter than 3000 A.

Standard lamps in the larger sizes radiate small but significant amounts of near ultraviolet. The amount of energy in the ultraviolet increases more rapidly than the wattage, as can be seen from the table. For example, the 1000-watt lamp radiates 16 times as much energy in the 3200 to 3800 A region as the 100-watt lamp, instead of 10 times as much as might be expected. This is because it is possible to operate the higher-wattage filaments at higher temperatures than the lower-wattage filaments and still obtain the same lamp life. Thus the 1000-watt lamp operates at 2990°K, but the 100-watt lamp operates at only 2865°K.

The 1000-watt photoflood lamp which operates at a filament temperature of 3360°K radiates a considerably larger fraction of its output in the ultraviolet than any of the standard lamps. Because of its high temperature, however, its life is limited to 10 hr.

Drying and heat lamps which operate at low temperatures in the range between 2000 and 2500°K obviously emit very little ultraviolet.

The table shows that except in the case of the 1000-watt photoflood lamp the erythemal flux from incandescent lamps is quite insignificant. Even in this lamp only 0.3 per cent of its input is radiated in the ultraviolet, whereas the figure for mercury arcs may be as much as 25 per cent.

There are some ten thousand types of incandescent filament lamps. The radiation from all of them, however, can be calculated by application of the Stefan-Boltzmann and Planck laws or can be readily determined from curves such as Fig. 3, once the filament temperature and area are known.

TABLE 5

RADIATION FROM INCANDESCENT LAMPS

Type of Lamp	Color Temperature, °K	2800–3200 A		3200–3800 A		Total UV		Total Visible 3800–7600 A		Units of Erythemal Flux
		Watts	% of Lamp Watts	Watts	% of Lamp Watts	Watts	% of Lamp Watts	Watts	% of Lamp Watts	
40-w Standard	2750	0	0	0.01	0.03	0.01	0.03	2.9	7.2	2 *
100-w Standard	2865	0	0	0.06	0.06	0.06	0.06	9.8	9.8	7 *
500-w Standard	2960	0.006	0.001	0.46	0.09	0.47	0.09	59	12	67 *
1000-w Standard	2990	0.03	0.003	0.96	0.096	0.99	0.099	125	12.5	195 *
1000-w Photoflood	3360	0.17	0.017	3.1	0.31	3.27	0.33	185	18.5	1000 *
250-w Drying	2500	0	0	0.01	0.004	0.01	0.004	10	4.0	0 *
250-w Heat	2000	0	0	0	0	0	0	1.7	0.69	0
250-w Purple X	3100	0.006	0.003	0.28	0.11	0.286	0.113	24	0.09	100 *
500-w CX	3015					0.65	0.13	61.5	12.3	†
900-w Projection	3200					1.17	0.13	133.2	14.6	†
6.4-volt Auto (15.8 watts)	2905					0.016	0.1	15.5	9.8	†

* *Gen. Elec. Lamp Bulletin* LD-1.

† B. T. Barnes, W. E. Forsythe, and W. J. Karash, *Gen. Elec. Rev.*, **42**, 540 (1939).

BLACK-LIGHT INCANDESCENT LAMPS

Although incandescent lamps are relatively weak sources of ultraviolet, they are used in some applications for exciting fluorescence by near ultraviolet. For this purpose it is essential to filter out the intense visible radiation in order to be able to detect the weak fluorescence.

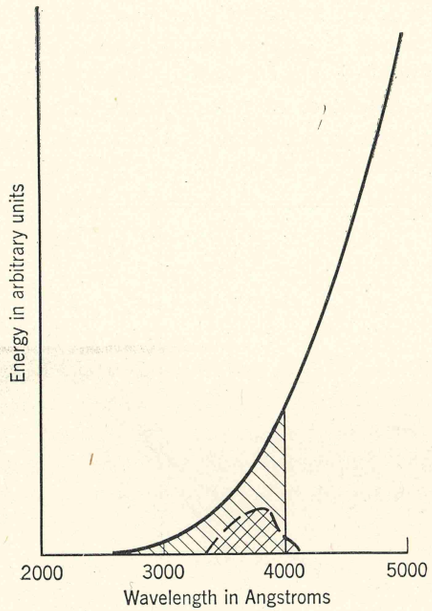

FIG. 4. Effect of filter on radiation from incandescent lamp. Shaded region, available ultraviolet energy; cross-hatched region, ultraviolet transmitted by filter.

This is done by enclosing the lamp in a bulb of red-purple Corex or some similar glass which transmits the near ultraviolet in the 3650 A region but is nearly opaque to the visible radiation. These lamps are often referred to as black-light lamps.

An ultraviolet filter of this kind is fairly efficient for use with a mercury arc. The only strong line in the near ultraviolet is at 3650 A, and the 5872 filter, for instance, transmits about 48 per cent of this radiation. In the case of the incandescent lamp, however, Fig. 4 shows that the ultraviolet filter transmits only about one-third of the available ultraviolet energy.

The 250-watt purple X lamp listed in Table 5 is a black-light lamp useful for the examination of fluorescent minerals or for the examination

of laundry marks made with fluorescent ink or wherever a small quantity of near ultraviolet is required and efficiency is not an important consideration. Small incandescent lamps covered with thimbles of ultraviolet-transmitting glass are also used to excite the fluorescent markings on the instrument dials on automobile dash boards.

The black-light lamps used for illuminating instrument dials on airplanes are usually of the fluorescent type (see Chapter 7).

Effect of Operating Voltage

The ultraviolet output of an incandescent lamp is very sensitive to changes in operating voltage. This is because of the rapid change in

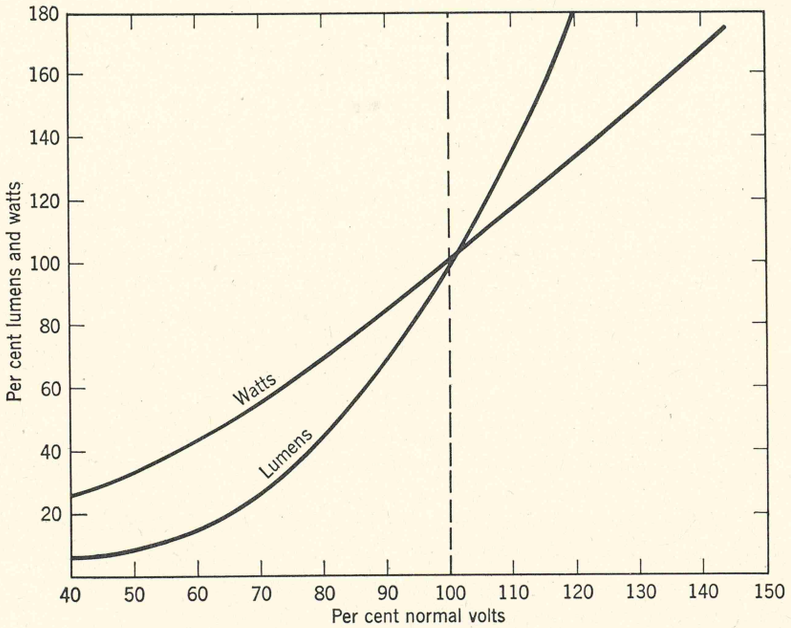

Fig. 5. Effect of voltage variation on output of incandescent lamp. (*Gen. Elec. Lamp Bulletin* LD-1.)

ultraviolet output with change in filament temperature. Figure 5 shows the relation between lamp operating volts and lamp watts. The wattage increases as the 1.54 power of the voltage. The light output, however, as shown in the figure, increases much more rapidly than the wattage because of the shift in the energy distribution towards shorter wavelengths with increase in filament temperature. The light output actually increases with the 3.38 power of the voltage. Thus an increase of 10 per cent in operating voltage will increase the lamp wattage 18 per cent and the light output 35 per cent. The increase in ultraviolet output will be even greater.

Photoflash Lamps

Photoflash lamps, although constructed in a form superficially like that of lamps, are actually combustion sources in which aluminum is burned in oxygen. They are glass bulbs containing a mass of very fine aluminum wire or foil in an atmosphere of oxygen. A primer on the filament ignites the aluminum, which because of its extreme thinness burns with great rapidity and reaches a very high temperature. The energy distribution of the radiation is approximately the same as that from a black body at 3500°K. The peak brightness of the flash is considerable, as much as 4,800,000 lumens for one type of lamp. The duration of the flash, however, is of the order of a few milliseconds so that the total light in the above instance is 93,000 lumen-seconds. From the curve of Fig. 3 (Holladay) it can be seen that photoflash lamps radiate about 0.8 per cent of their energy in the near ultraviolet.

Table 6 gives the energy in various wavelength bands for some of the same lamps shown in Table 5 in terms of the intensity on a unit area at

TABLE 6

Radiation from Incandescent Lamps

Energy in Various Wavelength Bands Falling on a Unit Area at a Distance of 1 Meter from the Lamp

	Microwatts per Square Centimeter		
Type of Lamp	2800–3200 A	3200–3800 A	3800–7600 A
40-w Standard	.....	0.08	22.5
100-w Standard	.....	0.45	75
500-w Standard	0.045	3.5	440
1000-w Standard	0.28	8.8	1160
1000-w Photoflood	1.4	25	1580
		2800–3800 A	
500-w CX (Corex bulb)		5.6	4950

a distance of 1 meter from the lamp. These values have been calculated from Table 5 and from candlepower distribution curves. The data in the first column show that the energy in the therapeutic range is quite

small. For example, the intensity at 1 meter from the 1000-watt photoflood lamp is 1.4 μw per cm^2, whereas the intensity from mercury arcs may be several hundred times as much.

Pointolite Lamp

In the Pointolite lamp an arc is used to heat a small tungsten ball to incandescence. The arc in an inert gas is formed between a hot cathode and the small tungsten ball which serves as anode. The bombardment by the electron current from the filament brings the ball to a temperature of 2920°K, thus providing a very concentrated source at a very high temperature. Although this is truly an arc, practically all the radiation comes from the incandescent tungsten ball.

Exploded Wires

Incandescence at a very high temperature has been obtained by exploding fine wires by means of a condenser discharge.[2] A condenser charged to a high potential is suddenly discharged through a very fine wire. The discharge explodes the wire, and a very high temperature is reached for a brief interval. When a 0.4-μf condenser charged to 26,000 volts is discharged through a wire of the order of 0.1 mm diameter, the gases formed attain a pressure of the order of 20 atmospheres and a temperature of the order of 15,000°C. The intrinsic brightness of the explosion as a source of light is very high "being apparently much greater than that of the solar surface." The continuous spectrum extends into the extreme ultraviolet. No measurements are available of either the relative or the absolute intensity.

Flames

Most flames burn at such low temperatures that their ultraviolet output is insignificant. Their luminosity is largely due to incandescent particles of carbon set free during combustion. Flame temperatures vary considerably with conditions of combustion. The energy distribution in the spectrum of a flame is approximately the same as that of a black body at the same temperature. The radiation from an acetylene flame is approximately the same as that from a black body at 2360°K. From Fig. 3 (Holladay) it is evident that the ultraviolet (or even the blue radiation) from most flames is very small.

Temperatures as high as 3500°C are reached (and sustained) in oxyacetylene flame. Although not used as a practical source of ultraviolet, the high temperature together with a relatively large radiating

surface could result in a high intensity of ultraviolet and should be guarded against.

Combustion of magnesium in air gives a higher temperature (3700°K color temperature) than hydrocarbon flames; hence its use in photography. No data are available on the energy distribution or the absolute values of its spectrum.

Summary

Incandescent lamps are very weak sources of ultraviolet except in the near ultraviolet region. The most efficient incandescent lamp for the production of ultraviolet is the 1000-watt photoflood lamp with a life of only 10 hr. (Yet the total ultraviolet radiation of less than 3800 A emitted by this lamp is only about 3 watts, whereas a 100-watt S-4 sunlamp emits 5.7 watts.) Together with the low ultraviolet efficiency goes a relatively large amount of visible radiation so that, where ultraviolet is required to the exclusion of visible radiation, a greater problem is encountered in the use of incandescent lamps than in the use of mercury arcs. For example, the ratio of visible to ultraviolet energy is about 2 for the sunlamp and 60 for the photoflood lamp. On the other hand, the simplicity of the incandescent lamp is an advantage wherever its output is sufficient to warrant its use.

References

1. L. L. Holladay, *J. Optical Soc. Am.*, **17**, 329 (1928).
2. J. A. Anderson, *Astrophys. J.*, **51**, 47 (1920).

4 Solar Radiation

The radiant energy received from the sun is responsible for the development and continued existence of life on the earth. The distribution as well as the total amount of energy in the solar spectrum is a very important factor in our environment. The tropics and the polar regions owe their properties and their distinctive forms of life to differences in the quantity and quality of the radiation which they receive from the sun. The entire course of terrestrial evolution has been influenced by the gradual changes in the character of the radiation which reached the earth's surface through the changing gaseous atmosphere as the earth cooled to its present state.

The sun is an incandescent mass having a surface temperature of 6000°K. Its central temperature has been calculated to be 20 million degrees, and its central pressure 160 billion atmospheres. The source of this tremendous heat production has been the subject of much speculation. A nuclear reaction which is adequate to explain it has been suggested by Bethe. The reaction is a cyclic one in which helium is formed from hydrogen. When this reaction takes place, some mass is annihilated with the consequent evolution of a tremendous amount of energy which appears as heat. According to this point of view, the sun has been likened to a "nuclear pot in which helium is being cooked from pure hydrogen." [1]

The radiation from the sun is of great interest to meteorologists as well as to astronomers and physicists. The intensity of the solar radiation as it would be found by an observer outside the earth's atmosphere at the earth's mean solar distance is called the solar constant. The average value is 1.93 cal per cm^2 per min or 0.135 watts per cm^2. This is equivalent to 1130 watts or 1.5 horsepower on a square yard. About two-thirds of this energy actually reaches the surface of the earth, the remainder being reflected, scattered, or absorbed in the atmosphere. The sun supplies to the United States about 2000 times as much heat energy as is now supplied by coal, oil, and gas.[2]

Daily measurements of solar radiation have been carried on continuously at the Smithsonian Institution in Washington, D. C., and its field stations for nearly 50 years. These measurements show that, in addition to the modification of the solar radiation by local changes in atmospheric conditions, there are also small periodic variations in the amount

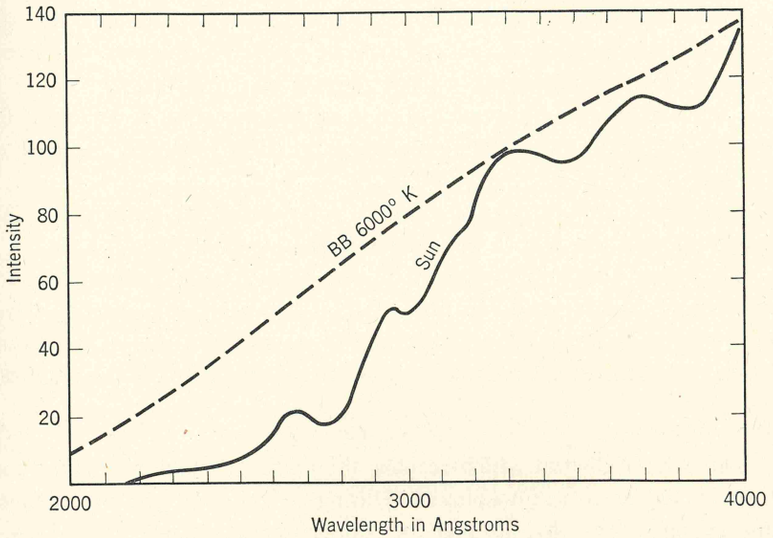

FIG. 1. Comparison of solar energy distribution in the ultraviolet outside the earth's atmosphere with that of a black body at 6000°K. (E. O. Hulburt, *J. Optical Soc. Am.*, **37**, 414, 1947.)

of radiation coming from the sun. A better understanding of these fluctuations may be an aid to the long-range prediction of weather. The fluctuations observed are of the order of 1 per cent. They are not entirely random but show a gradual rise and fall with an 11-year period which also coincides with sunspot activity. Other periodicities have also been noted. Some of these periodicities have been correlated with terrestrial phenomena, such as fluctuations in the level of the River Nile and of the Great Lakes; the abundance of cod and mackerel and other animals.

Since the sun is an incandescent body, it is to be expected that its spectrum would be very much like that of a black body at the same temperature as the sun. To some extent this is true, as can be seen from Fig. 1,[3] which shows the calculated energy distribution in the ultraviolet for a black body at 6000°K in comparison with the solar energy distribution as it would be observed outside the earth's atmosphere. The

black-body curve is a smooth one; the solar radiation has superimposed on it an absorption spectrum of the gases in the solar atmosphere. This in part accounts for its departure from the black-body curve. It can be seen from the figure that the two are in fair agreement except in the far ultraviolet where the solar radiation is less intense. The solar spectrum is vastly complicated by the radiation from the corona. Recent observations [4] indicate that this luminous atmosphere surrounding the sun may be at a temperature of as much as 1,000,000 degrees. It is believed to be responsible for a large portion of the ultraviolet output of the sun. When the ultraviolet portion of the spectrum is corrected for the absorption in the earth's atmosphere, it is fairly closely represented by that of a black body at 4000°K.

Only about 50 per cent of the total solar radiation lies in the visible spectrum, and less than 5 per cent is in the ultraviolet.

The solar ultraviolet intensity at the earth's surface depends on a number of factors including time of day, time of year, latitude, elevation above sea level, atmospheric turbidity, and thickness of the ozone layer. A common denominator for the first four factors is the air mass.

Air Mass

The solar radiation which reaches the earth's surface must first pass through the earth's atmosphere. During its passage it is modified by absorption. It is obvious that the total absorption must depend upon the amount of atmosphere, that is, the thickness of the layer of atmosphere which the radiation traverses. In addition, of course, the absorption depends upon local conditions such as clouds, fog, haze, dust, and smoke.

From Fig. 2 it can be seen that when the sun is directly overhead as at A (in the zenith) the length of the path of the radiation through the atmosphere oa is a minimum. When the sun is in any other position such as B, the path of the radiation through the atmosphere ob is oblique and hence longer than oa. The relative amount of atmosphere traversed is called the air mass and is taken as unity when the sun is in the zenith. For any other position of the sun the air mass is greater than 1. The angles α and β are known, respectively, as the solar zenith distance and the solar elevation. Their sum is 90°.

If we make the simplest assumptions, the air mass is proportional to the secant of the sun's zenith distance, that is, to the secant of α. Near the horizon factors such as the curvature of the earth and the refraction

of the atmosphere must be taken into account. The result is that the values of air mass at large zenith angles (low solar altitude) are less

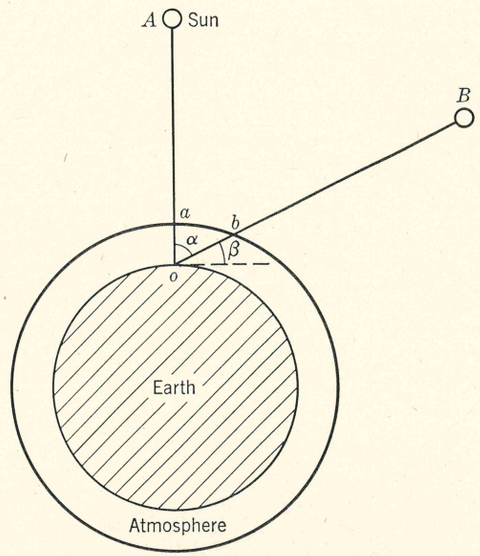

FIG. 2. Relation between air mass and solar elevation.

than those calculated by the simple secant law. Table 1 shows the values of air mass corresponding to various values of zenith distance according to the simple secant law and according to the formula of Bemporad.

TABLE 1

Solar altitude	5	10	20	30	40	50	60	70	80	90
Air mass (Bemporad)	10.40	5.60	2.90	2.00	1.55	1.30	1.15	1.06	1.02	1.00
Secant	11.47	5.76	2.92	2.00	1.56	1.31	1.16	1.06	1.02	1.00

From the foregoing considerations it is evident that the air mass at any point on the earth's surface depends upon the elevation of the sun above the horizon. This is a function of the time of the day and the season of the year. Figure 3 taken from Benford [5] shows the altitude of the sun at various hours of the day throughout the year at north latitude, 30°, 40°, 50°, and 60°. From this data and Table 1 the air mass may be determined for any hour and season. Thus at noon at latitude 40° the altitude of the sun varies from 26° in January to 73° in June, corresponding to air masses of 2.3 and 1.05, respectively.

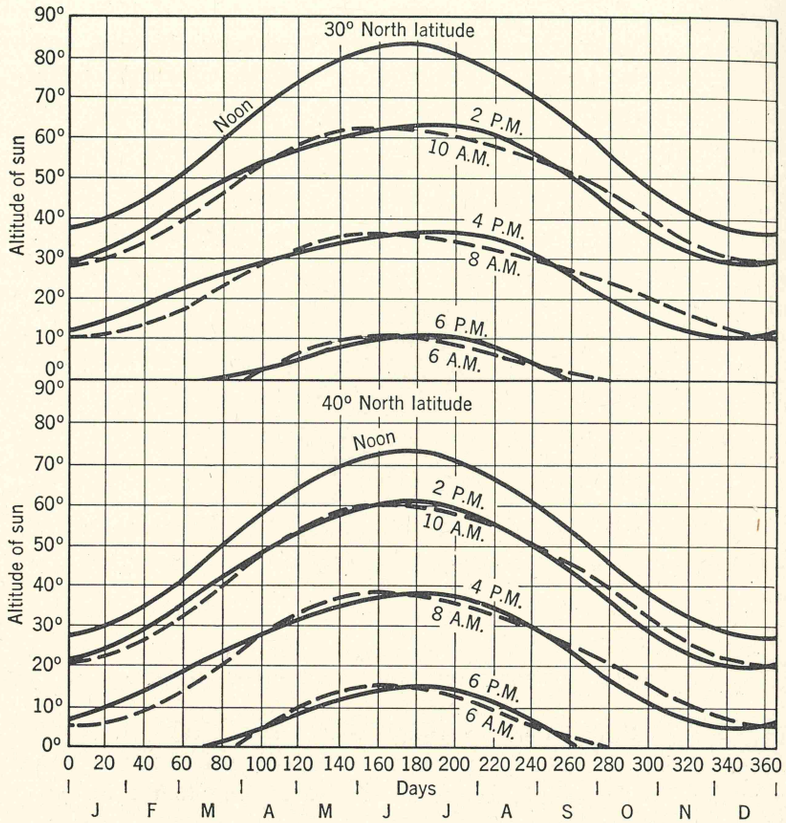

FIG. 3*a*. Solar altitude at various hours of the day throughout the year at north latitude 30° and 40°. (F. Benford, *Illum. Eng.*, **42**, 527, 1947.)

EFFECT OF ATMOSPHERIC ABSORPTION ON SOLAR SPECTRUM

The absorption of radiation by the atmosphere follows a simple exponential law. If I_0 is the initial intensity of the radiation, the intensity after traversing a unit air mass will be aI_0. After traversing an air mass of m units the intensity I will be

$$I = I_0 a^m$$

where a = the transmission coefficient for air mass = 1.
m = the air mass.

The transmission coefficient a varies with the wavelength of the radiation under consideration. In general, it is greater for short than for long wavelengths. Table 2 gives values of transmission coefficients for various wavelengths at air mass unity. These values correspond to

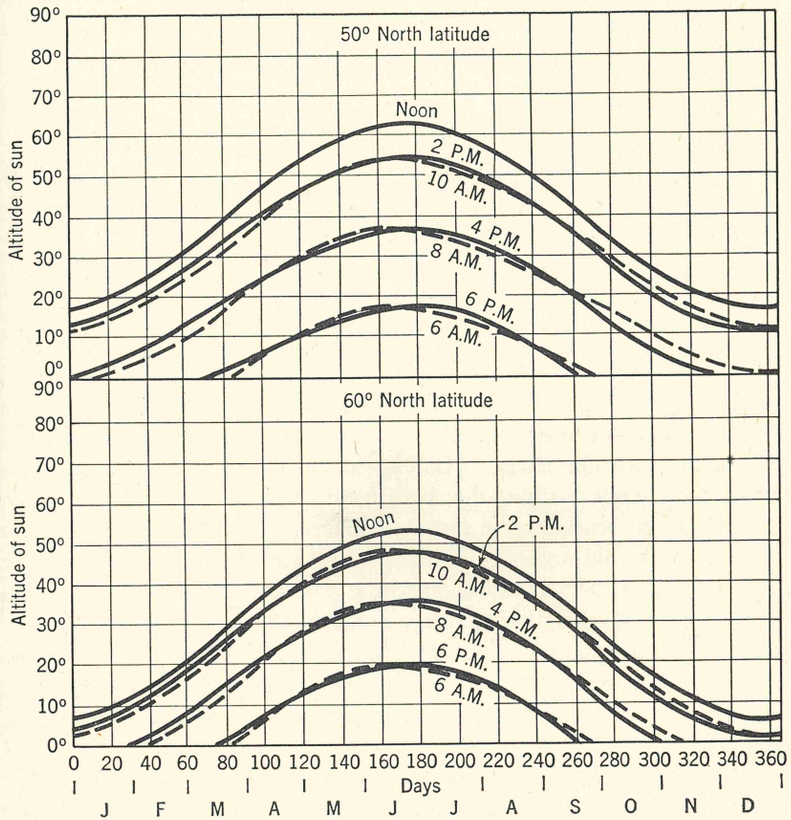

FIG. 3*b*. Solar altitude at various hours of the day throughout the year at north latitude 50° and 60°. (F. Benford, *Illum. Eng.*, **42**, 527, 1947.)

clear weather at 5500 ft altitude and to average cloudless weather at sea level as observed at Washington. They are for a smooth transmission curve and do not take into account atmospheric absorption bands. The effect of the decreased transmission at lower altitudes is most marked for the shorter wavelengths.

The effect on the solar spectrum of variation in absorption with wave-

TABLE 2

VALUES OF TRANSMISSION CONSTANT FOR AIR MASS UNITY *

Wavelength	*a*	*b*	Wavelength	*a*	*b*
0.295	0.20	0.00	0.405	0.77	0.52
0.305	0.36	0.03	0.450	0.84	0.62
0.315	0.45	0.07	0.500	0.89	0.71
0.325	0.51	0.13	0.600	0.93	0.77
0.336	0.56	0.20	0.700	0.96	0.85
0.346	0.60	0.26	0.800	0.96	0.90
0.355	0.64	0.31	0.900	0.97	0.92
0.366	0.67	0.37	1.00	0.97	0.93
0.378	0.71	0.42	2.00	0.96	0.94
0.391	0.74	0.48	2.40	0.95	0.94

* From W. E. Forsythe, *Measurement of Radiant Energy*, McGraw-Hill Book Co., New York, 1937, page 77.

a. Clear weather at 5500 ft altitude.

b. Average cloudless weather at sea level, as observed at Washington, D. C.

length, is illustrated in Fig. 4, which shows the energy distribution in the solar spectrum as observed at the earth's surface, corresponding to various values of air mass. The curves show that as the air mass increases the energy reaching the earth's surface decreases, because of the absorption and scattering in the atmosphere. But this effect is by no means uniform throughout the spectrum and is most marked at the shorter wavelengths. In addition to the generally increased absorption at the shorter wavelengths, there are numerous regions of strong absorption called absorption bands. In the far infrared (not shown in the figure) there is a very strong absorption band at 2.5 μ due to CO_2. There is also a strong absorption band at the long-wave edge of the visible spectrum due to oxygen.

It has already been noted that in the ultraviolet the solar radiation at the earth's surface differs markedly from black-body radiation. The atmospheric absorption is very strong in this region. It can be seen from Fig. 1 that for a black body at 6000°K the intensity at 3000 A is 61 per cent of that at 4000 A, falling off to 9 per cent at 2000 A. The solar radiation, however, as can be seen from Fig. 1, falls off much more rapidly than this, and no energy is detectable at the earth's surface at wavelengths shorter than 2900 A.

The intensity of sunlight is primarily a function of the height of the sun above the horizon. It is also affected to a lesser degree by differences in the distance of the earth from the sun and differences in the clearness of the atmosphere.

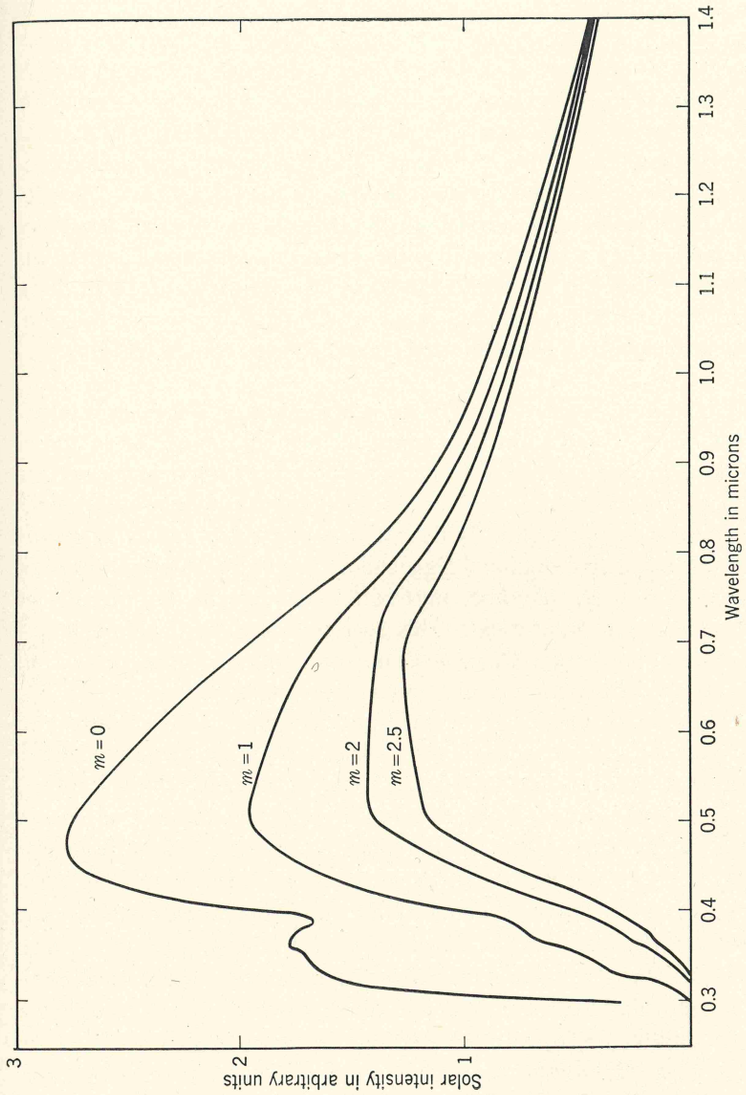

FIG. 4. Energy distribution in the solar spectrum as observed at the earth's surface for various values of air mass. (Calculated from W. E. Forsythe, *Measurement of Radiant Energy*, McGraw-Hill Book Co., New York, 1937.)

Atmospheric Absorption and Scattering

The attenuation of visible radiation in clear air is very small as can be seen from Table 2. At the wavelength 5000 A in the visible spectrum nearly 90 per cent of the energy passes through the entire earth's atmosphere. The attenuation over distances of a few meters may be entirely neglected in the wavelength region 3000 to 10,000 A. At wavelengths less than 3000 A, however, the attenuation becomes appreciable and increases rapidly towards shorter wavelengths. Dawson, Granath, and Hulburt [6] studied it in this region over a path length of 400 meters. They found that it is the same day and night and is unaffected by changes in humidity. It does, however, increase with haze. The absorption coefficients are given in Chapter 6 on transmission. The transmission of 1 meter of air is about 10 per cent at 2050 A and 99 per cent at 2200 A.

Investigation in greater detail of the attenuation or decrease in intensity of a beam of radiation in passing through the atmosphere shows that several processes are involved. The two most important ones are absorption and scattering. Part of the attenuation or decrease in intensity is due to true absorption in the atmosphere which results in a portion of the original radiation being changed into some other form of energy, such as heat. Another part of the decrease in the intensity of the beam is due to scattering. This scattered radiation, although lost to the original beam, is not changed into some other form of energy but merely diverted from its original direction of propagation.

The scattering is produced by small particles, such as dust and water droplets in the air, as well as the gas molecules of the atmosphere. Each of these particles acts as a center from which radiation is scattered in all directions. Lord Rayleigh showed that the amount of energy scattered by particles much smaller than a wavelength in diameter is inversely proportional to the fourth power of the wavelength. Accordingly, scattering is most pronounced for the short wavelengths in the blue and ultraviolet. It is the scattering of the short wavelengths which accounts for the blue color of the sky. If light only reached the earth in the straight-line path from the sun, the sky would appear black since no light could come from it. Scattering, however, diverts some of the radiation from the straight-line path, and as a result of repeated scattering radiation appears to come from all parts of the sky. Since the effect is most pronounced for the short wavelengths, the sky appears predominantly blue. There is also a strong ultraviolet component in the scattered radiation which will be discussed in greater detail on page 118.

The quantitative expression for the attenuation of radiation in passing through an absorbing or scattering medium is

$$I/I_0 = e^{-at}$$

where I_0 = the initial intensity.
I = the intensity after traversing a thickness t.
a = the attenuation coefficient.

If we consider the attenuation process as partly scattering and partly absorption, the attenuation coefficient a may be written

$$a = \alpha + \beta$$

where α and β are, respectively, the scattering and absorption coefficients so that the expression becomes

$$I/I_0 = e^{-(\alpha+\beta)t}$$

Detailed investigation shows that the attenuation in air at short wavelengths is greater than can be accounted for by Rayleigh scattering alone, i.e., the attenuation is in part due to Rayleigh scattering and in part to true absorption. Above the wavelength 3000 A the attenuation is due mostly to Rayleigh scattering. Further details are given in Chapter 5.

Ozone

Although Fig. 4 shows that no solar energy of wavelengths shorter than 2900 A reaches the earth's surface, the values of the absorption coefficient measured in the lower atmosphere indicate that this cannot be entirely due to absorption by air. The entire atmosphere is equivalent to a thickness of 8 km which would only be sufficient to reduce radiation of wavelength 2800 to 1 per cent of its initial intensity. Accordingly, the entire absence of wavelengths shorter than 2800 A must be due to some other factor. It is believed that this factor is the absorption by a blanket of ozone in the upper atmosphere. This region is beyond the reach of ordinary flight, but it has been studied in considerable detail by means of radio sonde and rockets. Radio sonde are small free balloons which carry meteorological instruments including photoelectric cells to very high altitudes. These instruments automatically report their observations back to ground stations by radio. By this method altitudes of 78,000 feet have been attained. Figure 5 shows a radio sonde.

The radio sonde measurements show a variation in ultraviolet intensity with altitude which supports the view that ozone is formed from the ogygen in the air by solar energy of wavelength 2000 A and shorter. Ozone, however, is a strong absorber between 3000 and 2200 A and so screens out radiation in this region. (The absorption coefficients for ozone for various wavelengths are given in Chapter 5.) The total amount of ozone formed is equivalent to a layer only about 3 mm thick at normal temperature and pressure, but owing to its tremendous absorption its effects are very pronounced.

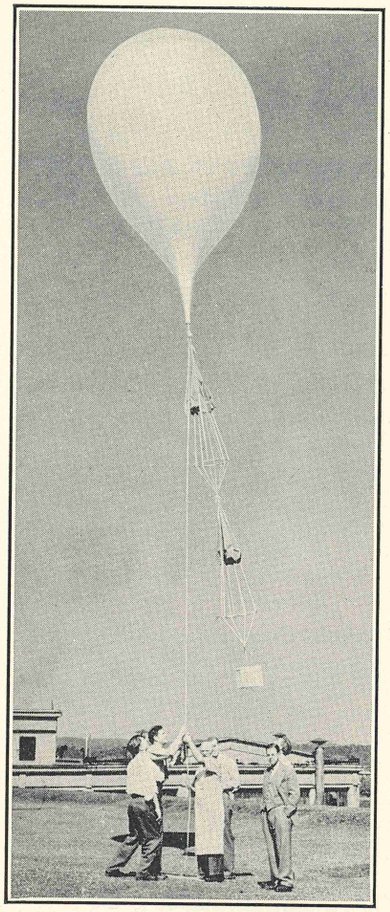

FIG. 5. Radio sonde. (Courtesy of General Electric Co.)

The concentration of ozone is not uniform throughout the atmosphere but passes through a maximum at an elevation of about 24 km. At this elevation the amount of ozone per kilometer is equivalent to a layer 0.015 cm in thickness. Most of the ozone is concentrated here within a region of about 5 km. The concentration falls to very low values at ordinary terrestrial levels. In the country, near the surface of the ground it is a few one-hundredths of a part per million. (The threshold concentration of ozone for a keen sense of smell is 0.01 ppm by volume.) Figure 6 shows the ozone content of the atmosphere as a function of altitude expressed in terms of the thickness of the equivalent ozone layer per kilometer of atmosphere.

The results obtained by different methods are not in quantitative agreement, although they give approximately the same value for the position of the maximum. The curves of Fig. 6 represent the extremes of variation in ozone concentration with altitude determined by different methods. Ozone is the only stratified gas in the earth's atmosphere. The total amount of ozone is about the same as that of the hydrogen present in the atmosphere and several times as much as the xenon.

The concentration is greater the higher the latitude. There is also a seasonal variation. The concentration is greatest in the late winter and early spring and least in the late summer and early fall. The seasonal variation almost disappears at the equator, where the concentration is practically constant throughout the year. There are also marked variations in the concentration of ozone with varying local meteorological conditions. The concentration is higher in the morning than in the afternoon. There is no correlation between ozone concentration and surface pressure patterns. Variations in this ozone blanket are responsible to a large extent for some of the variation in the amount of short-wave ultraviolet reaching the earth's surface.

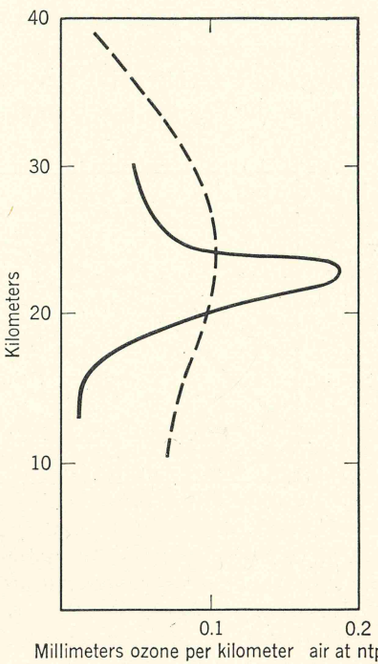

FIG. 6. Ozone concentration of the atmosphere as a function of altitude. These curves show the extremes measured by different observers.

A concentration of ozone of 0.1 ppm is objectionable and irritating to the mucous membranes of the nose and throat in most persons. Higher concentrations are toxic. Concentrations of more than 1 ppm produce harmful effects on plants. Concentrations of a few parts per million are used in food storage to retard the growth of bacteria and molds.

SKY RADIATION

As a result of scattering in the atmosphere, a very significant amount of ultraviolet reaches the earth's surface from the sky as well as directly from the sun. On a clear day at some hours the amount of ultraviolet falling on a horizontal surface from the sky may be greater than the amount directly from the sun, and at all hours it is comparable in

amount with that from the sun. This is illustrated in Fig. 7 which shows the radiation received on a horizontal surface from the sun and from the sky at various hours throughout the day. As the elevation of the sun becomes greater both the sky and the direct components increase, reaching a maximum at noon and falling off again in the afternoon as the elevation of the sun becomes less. The direct component changes more rapidly with elevation than the sky component. In the middle of the day the two components are approximately equal, but in

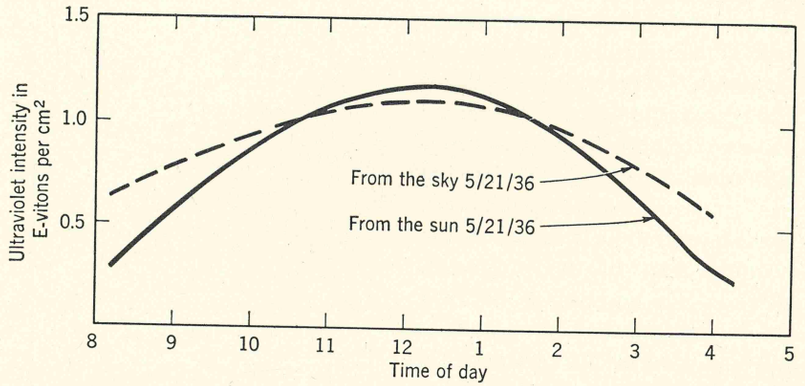

FIG. 7. Intensity of ultraviolet radiation on a horizontal surface from the sun and from the sky at various hours throughout the day. (M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., New York, 1946.)

the early morning and in the late afternoon the sky component is considerably larger. It is this very large sky component which is responsible for the fact that it is possible for the skin to be severely sunburned even though shielded from the direct sun at places such as beaches where a large area of the sky is exposed. The relative value of the two components varies with the season and with the turbidity of the atmosphere.

There are only a few hours during the middle of the day "when the erythemally weighted ultraviolet energy from the sun on a horizontal plane exceeds that from the sky." The angular zone 50° from the zenith contributes more than half of the erythemal ultraviolet received from the sky on a horizontal plane during the summer months.

Figure 8 shows the ratio of the sky component to the direct component as a function of solar altitude. (See Fig. 3 for solar altitude.) This ratio applies only to horizontal surfaces. The direct solar radiation intensity on a surface is proportional to the cosine of the angle of inci-

dence, so that the intensity of the direct radiation at low altitudes is greatly decreased for this reason, as well as on account of the increased air mass.

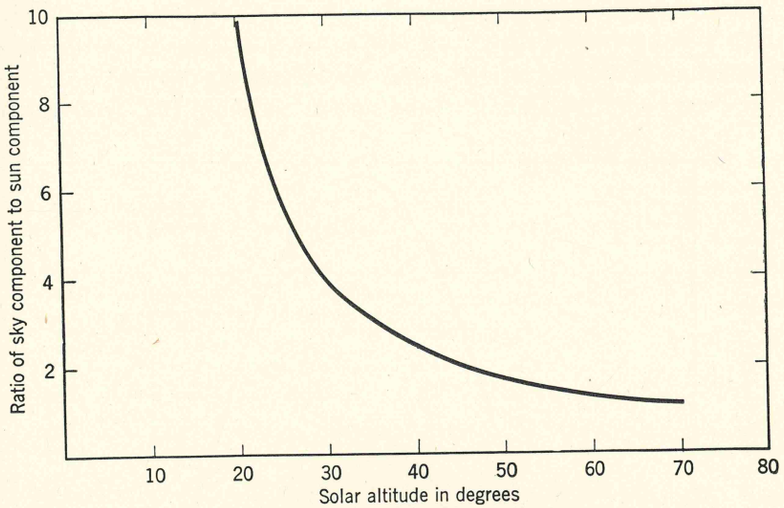

FIG. 8. Ratio of sky component to direct solar radiation as a function of solar altitude. (M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., New York, 1946.)

The radiation from different 10-degree zones of the sky is shown in Fig. 9. The upper zones contribute considerably more ultraviolet energy to a horizontal surface than the lower zones. The intensities falling on a surface perpendicular to each sky area do not fall off nearly so rapidly

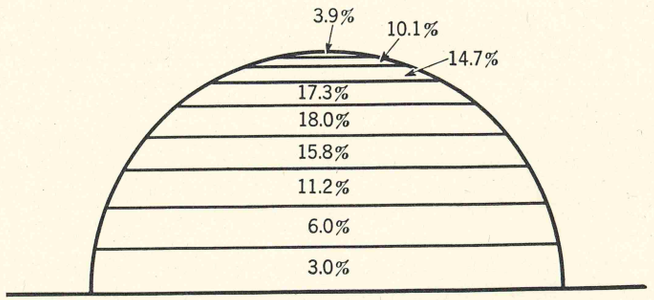

FIG. 9. Intensity of radiation falling on a horizontal surface from different 10-degree zones of the sky. (M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., New York, 1946, page 52.)

with distance from the zenith as do those on a horizontal surface. According to Luckiesh an area 70–80° from the zenith contributes about half as much energy in a direction perpendicular to the sky area as an equal area 0–10° from the zenith.

Daily Variation

The intensity of ultraviolet varies throughout the day, increasing and decreasing with the altitude of the sun, as shown in Fig. 10 from Coblentz and Stair.[7] The total intensity of ultraviolet of wavelength less than 3132 A from the sun and sky incident on a horizontal plane on four very clear days at different seasons in Washington, D. C., is shown.

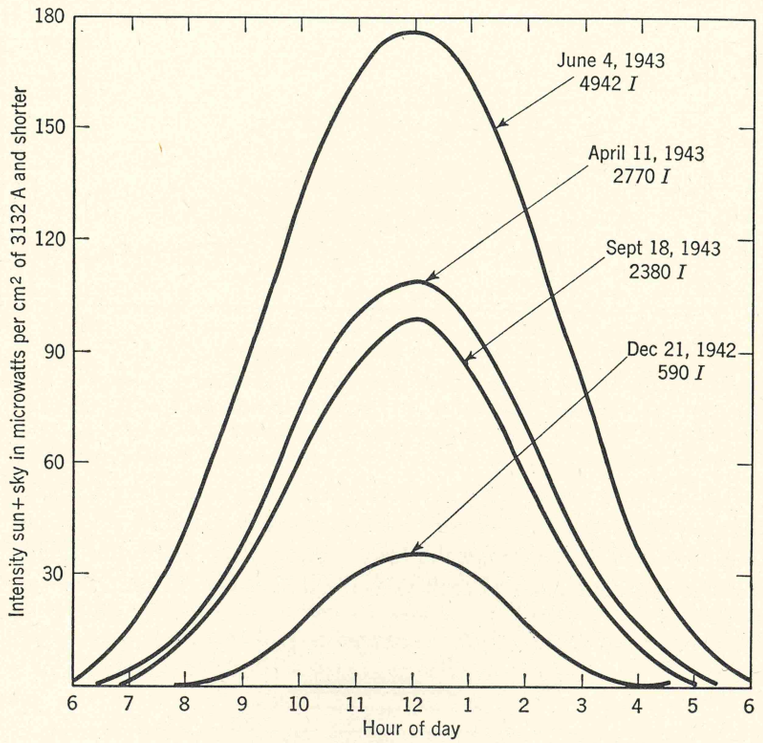

Fig. 10. Total intensity of ultraviolet of wavelength less than 3132 A from the sun and from the sky incident on a horizontal plane on four very clear days at different seasons in Washington, D. C. (W. W. Coblentz and R. Stair, *J. Research Natl. Bur. Standards,* **33,** 21, 1944.)

These curves show that the ultraviolet intensity in the early morning and late afternoon hours is very small compared with that in the middle of the day. They also show the seasonal trend discussed in the next section. The figures on the curves give the integrated values for each curve as measured by a photoelectric tube in terms of a standard unit *I*; each unit being equivalent to 780 μw-sec per cm^2.

It is important to note that not only does the amount of ultraviolet vary throughout the day but also the spectral quality of the radiation

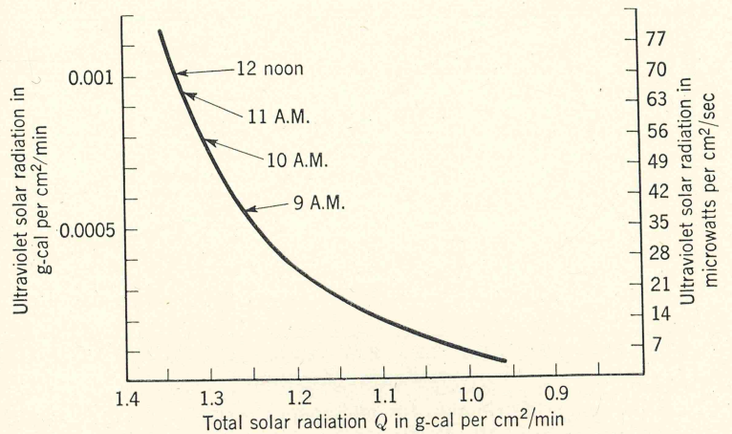

Fig. 11. Ultraviolet less than 3132 A relative to the total solar radiation. (W. W. Coblentz and R. Stair, *J. Research Natl. Bur. Standards,* **17,** 1, 1936.)

varies as well. It has been pointed out on page 110 that the absorption in the atmosphere is greater for the shorter wavelengths than for the longer wavelengths so that the former are relatively much more strongly absorbed than the latter at low solar altitudes. Figure 11 shows the relation between the amount of ultraviolet shorter than 3132 A and the total solar energy during the course of the day as measured in Washington, D. C., by Coblentz and Stair.[8] The figure shows that the ultraviolet in this region increases much more rapidly with the height of the sun than the total solar energy, doubling in intensity between 9 and 12 A.M., while the total solar energy increases only 7 per cent.

Solar Energy Distribution

The solar radiation at any particular location depends upon a wide variety of factors such as latitude, time of day, season, altitude, and

local atmospheric conditions. However, its general fundamental character (except in the ultraviolet) does not differ very much from place to place. The energy distribution curve for midsummer noonday sun on a clear day in Washington, D. C., is shown in Fig. 12. There is no energy of wavelength shorter than 2950 A. The energy rises rapidly with increasing wavelength to a maximum at about 5000 A and then decreases gradually. Table 3 gives the energy distribution in the ultraviolet as it would be observed outside the earth's atmosphere, and at

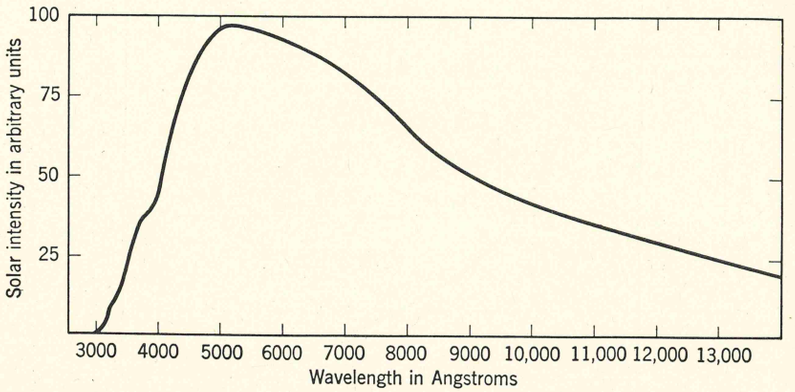

FIG. 12. Solar energy distribution for midsummer noonday sun in Washington, D. C. (Calculated from W. E. Forsythe, *Measurement of Radiant Energy*, McGraw-Hill Book Co., New York, 1937.)

Washington, D. C. The table illustrates the increasingly large effect of atmospheric absorption at the shorter wavelengths.

One of the prominent features of the solar spectrum in the ultraviolet is the rapid decrease in energy with decreasing wavelength. This is illustrated by the measurements of Coblentz [9] which show that the solar radiation between 295 and 450 μ accounts for 10 per cent of the total incident radiation for air mass 1 at Washington, D. C., whereas that between 295 and 320 μ is only 0.12 per cent of the total and that between 295 and 310 μ is only 0.04 per cent. Similar calculations by Forsythe and Christison over a slightly different range show that the solar energy received for air mass 1 for wavelengths less than 3250 A is only 0.24 per cent of the total while that between 310 and 290 μ is 0.022 per cent of the total. The intensity at 2898 A is only one millionth of that at 3143 A for the sun at the zenith in mid-latitude.[10]

TABLE 3

ULTRAVIOLET SOLAR ENERGY DISTRIBUTION—MIDSUMMER NOONDAY SUN *

Wavelength in Angstroms	Microwatts per cm² per 10 A Band, Washington, D. C. M = 0	M = 1.05
2950	16	0
2975	32	1
3000	33	2
3025	34	3
3050	37	5
3075	39	6
3100	43	8
3125	45	10
3150	46	11
3175	48	13
3200	53	17
3225	63	23
3250	75	29
3275	86	31
3300	93	41
3325	97	43
3350	104	49
3375	106	50

* From W. W. Coblentz and R. Stair, *J. Research Natl. Bur. Standards*, **17**, 1 (1936).

Table 4 is based on measurements by Pettit at Tucson, Arizona. The second column of the table gives the energy in microwatts per cm² for 100 A bands centered on the wavelengths indicated in the first column for the sun in the zenith. The third column gives corresponding values which would be observed if there were no atmospheric absorption. The effect of the atmosphere is most marked towards the shorter wavelengths, as has been discussed above.

Table 5 gives the energy distribution as determined by Luckiesh in Cleveland, Ohio. The values in this table are measured over a 50 A band, whereas those in Table 4 are measured over a 100 A band. Accordingly, for comparison the values in Table 5 should be multiplied by a factor of 2. The second and third columns give the intensity of the sunlight and sky light, respectively, in 50 A bands centered on the wavelengths indicated in column 1; the fourth column gives the total radiation.

The greater scattering of the shorter wavelengths is well illustrated in

TABLE 4

SOLAR ENERGY DISTRIBUTION AT TUCSON, ARIZONA *

Wavelength in Millimicrons	Microwatts per cm^2 per 100 A Band	
	Sun in Zenith	No Atmosphere
700	8.3×10^2	10.5×10^2
600	12.4	15.7
550	14.2	18.2
500	15.2	19.9
450	14.7	20
420	11.7	16.4
400	10.9	16
390	7.3	11.1
380	5.9	9.2
370	5.9	9.7
360	5.5	9.6
350	4.6	8.5
340	4.2	8.6
330	3.8	8.7
325	3.5	8.9
320	2.4	6.8
315	1.8	6.1
310	1.1	4.5
305	0.71	4.1
300	0.29	4.1
295	0.08	2.4
292	0.03	1.1

* Based on E. Pettit, *Astrophys. J.*, **75**, 217 (1932).

this table. In the ultraviolet the scattered radiation or sky light is approximately equal to the direct sunlight. As the wavelengths increase the proportion of sky light to the direct sunlight decreases until at 7000 A it is only about 20 per cent.

These three sets of measurements, although made in different localities and by different methods, indicate intensities of the same order of magnitude.

According to Coblentz, "At a sea level station in midlatitude on exceptionally clear days, the noon hour intensity of biologically effective ultraviolet radiation of wave lengths less than 3132 A, incident directly from the sun and a small portion of the surrounding sky, varies from about 75 microwatts/cm^2 in June (air mass 1.05) to about 12 microwatts in December (air mass 2.1)." This figure is a useful one to keep in mind for practical purposes.

TABLE 5

SOLAR ENERGY DISTRIBUTION *

Intensity of energy in microwatts per square centimeter on a horizontal surface during midday on a typical clear day in midsummer in Cleveland, Ohio. Latitude 41.5°N, for each spectral band of 50 A centered at the various wavelengths. The intensity of illumination on the horizontal surface averaged about 8500 foot-candles of combined sunlight and sky light.

Wavelength	Sunlight	Sky Light	Total
3000	2.6	2.6	5.2
3100	24	23.5	47.5
3200	65	60	125
3300	108	96	204
3400	126	107	233
3550	144	115	259
3700	186	139	325
3850	192	136	333
4000	268	165	433
4100	339	209	548
4200	377	223	600
4300	404	213	617
4400	426	201	627
4500	453	216	669
4600	492	234	726
4700	514	229	743
4800	525	218	743
4900	525	207	732
5000	525	193	718
5100	508	184	692
5200	492	168	660
5300	514	162	676
5400	535	158	793
5500	535	154	689
5600	525	146	671
5700	525	138	663
5800	514	132	646
5900	508	124	632
6000	503	118	621
6100	492	113	605
6200	486	110	596
6300	475	107	582
6400	464	102	566
6500	459	97	556
6600	453	93	546
6700	459	92	551
6800	481	91	572
6900	475	89	564
7000	464	85	549

* M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946.

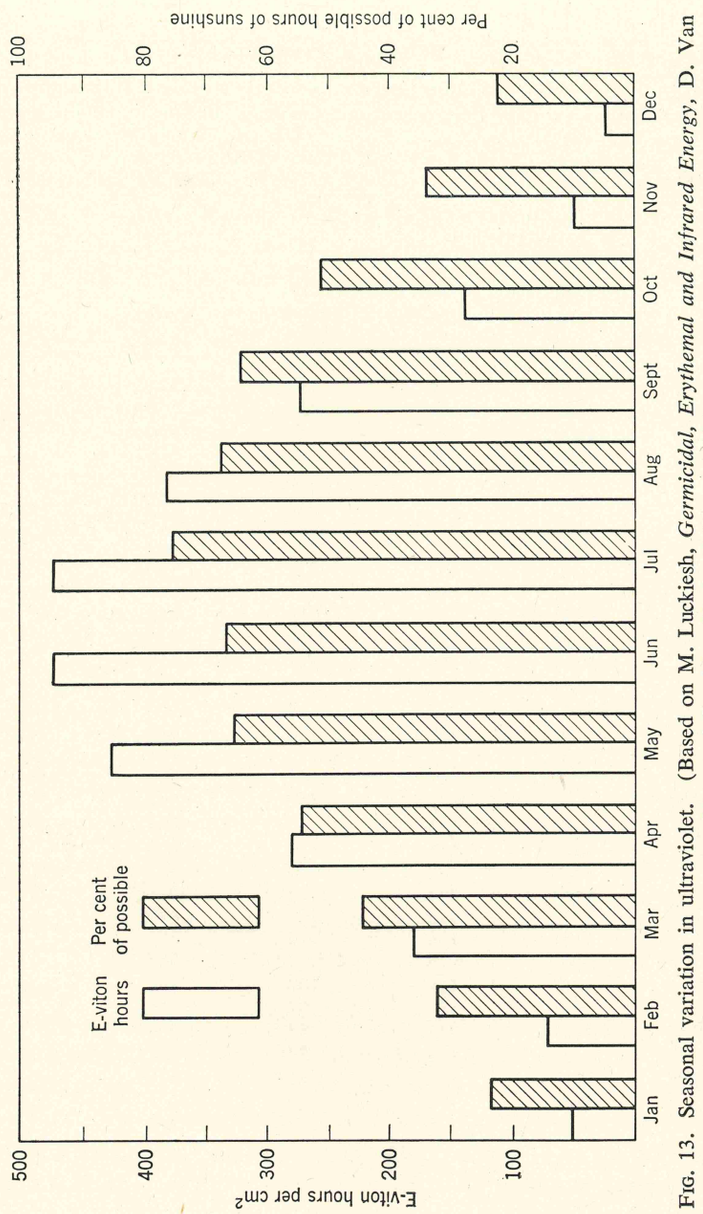

FIG. 13. Seasonal variation in ultraviolet. (Based on M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., New York, 1946, page 55.)

SEASONAL VARIATION

The seasonal variation of ultraviolet is shown in Fig. 13. This shows a plot of the average erythemally weighted ultraviolet from the sun and from the entire sky for each month of the year. These measurements are the average over 6 years of continuous observation. They are expressed in E-viton hours per square centimeter. (One E-viton is equivalent to 10 μw per cm^2 of radiation of wavelength 2967 A.) The per cent of the possible number of hours of sunshine observed for each month is also shown. The same data are tabulated in Table 6. The

TABLE 6 *

VARIATION OF AVERAGE HOURS OF ACTUAL SUNSHINE PER MONTH AND OF ERYTHEMAL ULTRAVIOLET ENERGY IN DAYLIGHT AS MEASURED ON A HORIZONTAL PLANE FOR A 6-YEAR PERIOD IN A SUBURB OF CLEVELAND, OHIO

	Hours of Sunshine			Erythemal Ultraviolet Energy	
Month	Possible	Average	Per Cent of Possible	E-Viton Hours/cm^2	Per Cent of Total for Year
January	295	71	24	51	1.8
February	297	98	33	72	2.5
March	370	167	45	182	6.3
April	401	221	55	280	9.8
May	452	298	66	430	15.0
June	455	305	67	476	16.7
July	461	350	76	476	16.7
August	429	292	68	386	13.5
September	374	243	65	277	9.8
October	343	178	52	143	5.0
November	295	103	35	55	1.9
December	285	66	23	30	1.0

* M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946.

last column of the table gives in addition the erythemal ultraviolet for each month in terms of the per cent for the entire year. The 4 months, May, June, July, and August, together supply about 62 per cent of the yearly total; November, December, January, and February, together supply only about 7 per cent of the yearly total. The month of December supplies about 1 per cent of the total for the year and about one-sixteenth as much as the month of June.

It can be seen from these figures that the integrated ultraviolet is

greatly reduced by cloudiness during the winter months and much less so in the summer.

Figure 14 is taken from observations by Coblentz over a 3-year period in Washington, D. C. It gives the average integrated monthly

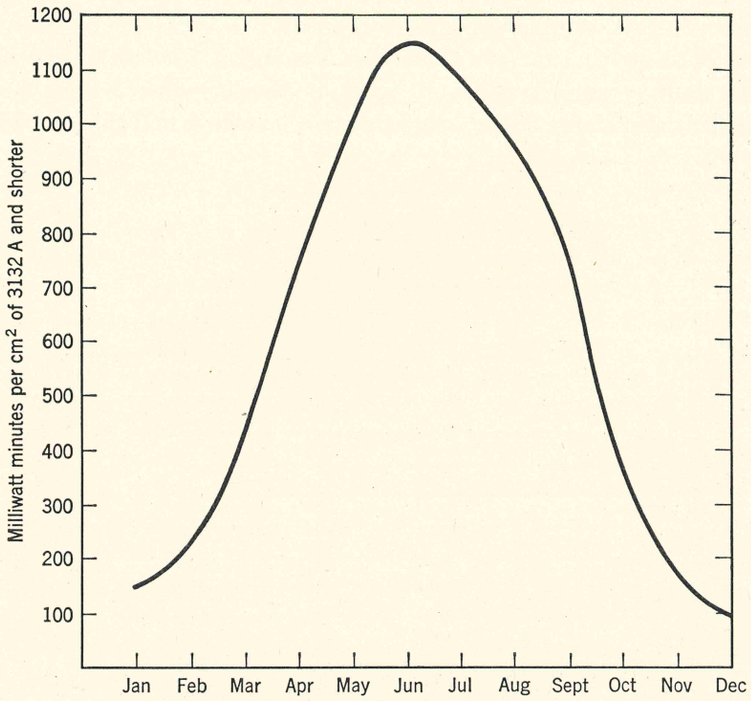

FIG. 14. Integrated monthly ultraviolet of wavelength less than 3132 A throughout the year. (W. W. Coblentz and R. Stair, *J. Research Natl. Bur. Standards,* **33,** 21, 1944.)

ultraviolet of wavelength less than 3132 A. These values like Luckiesh's show the seasonal trend. They also show higher values in the fall than in the spring, as is evident when months of comparable solar height are compared, for example, March and September, April and August, February and October, January and November. This is attributed to the lower concentration of ozone in the fall.

The seasonal trend is shown by the calculations of Forsythe and Christison * on the effect of air mass on solar radiation:

* W. E. Forsythe and F. Christison, *Gen. Elec. Rev.,* **32,** 662 (1929).

Air Mass at Latitude of Cleveland, Ohio	Date	Milliwats/cm² Ultraviolet and Visible	Milliwats/cm² Shorter than 325 mμ	Milliwats/cm² 310–290 mμ
1.07	June 21	97.6	0.21	0.019
1.5	February 15	64.0	0.07	0.0041
2.37	December 21	33.9	0.010	0.00017

The increase in air mass from 1.07 on June 21 to 2.37 on December 21 reduces the total solar energy received to about one-third. The absorption of shorter ultraviolet, however, is much more pronounced, and the energy of wavelengths shorter than 325 μ is decreased to 5 per cent, whereas that below 310 μ is decreased to less than 1 per cent. Thus not only does the quantity of the radiation change but its quality changes markedly. The steepness of the energy distribution curve on the short-wave side is responsible for this.

Coblentz has shown that there is a close relation between the intensity of the total incident radiation of all wavelengths and the intensity of the ultraviolet component between 2900 and 3150 A.

The average values for this ratio as observed over an 8-year period in Washington, D. C., are given below:

Month	Ratio Ultraviolet in mw-min/cm² to Total Radiation in g-cal/cm²
January	0.023
February	0.029
March	0.041
April	0.053
May	0.063
June	0.068
July	0.069
August	0.068
September	0.065
October	0.046
November	0.029
December	0.019

The total monthly radiation in gram-calories per square centimeter is ordinarily published by the weather bureau. This value multiplied by the constant given in the table gives the radiation between 2900 and 3150 A in milliwatt-minutes per square centimeter.

This is a very useful method of making an estimate of the total ultraviolet in this range.[11]

Geographical Variation

It is difficult to compare observations made in different localities by different observers because of the wide variation in methods used and the variation in spectral ranges covered. It seems probable, however, that under similar local atmospheric conditions the intensity of the solar radiation is the same in different latitudes for the same values of solar height. Coblentz made observations at 78° north latitude and found that "the intensity and biological effectiveness of ultraviolet and sky radiation in mid summer, in high latitudes (78°N) is not markedly different from that observed at the same solar height in December (M 2.10) in Washington." He found that on the clearest days in midsummer the intensity of ultraviolet solar and sky radiation ranged from 30 to 40 μw per cm^2 which is a significant value biologically.

For equal solar elevation the thinner ozone layer in the tropics would result in approximately 15 per cent greater intensity of ultraviolet. However, the greater turbidity of the tropical air works in the opposite direction. The net result is that there is little difference in intensity between the tropics and the temperate latitudes when allowance is made for the difference in solar elevation.

In addition to the variations due to latitude, local conditions such as cloudiness, haze, smoke, dust, fog, and humidity must be considered. All of these reduce the ultraviolet intensity in varying degrees. Light clouds and fog decrease the direct solar radiation but increase the scattered radiation. The net result, however, is a decrease in the total amount of radiation. For heavy clouds the decrease is much greater than for light clouds. The absorption of ultraviolet by the water vapor in the atmosphere is small compared with the absorption of infrared. Although fog decreases the total ultraviolet intensity, it has very little selective effect on the ultraviolet transmitted.

The atmospheric pollution by smoke and dust in large cities reduces the ultraviolet intensity at times to negligible proportions. Unlike fog and clouds these large particles of opaque material reduce the intensity of all wavelengths practically equally.

The total amount of ultraviolet, of course, depends upon the relative numbers of clear and cloudy hours. Table 7 shows the percentage of possible sunshine observed throughout the year at weather bureau stations in Washington, D. C., and Albany, N. Y. The records show that slightly more than half of the possible sunshine is actually observed in these two localities. Table 8 shows the maximum duration of sunshine for the longest and the shortest day in the year at various latitudes.

TABLE 7

Data on Average Number of Hours of Sunshine and Average Monthly Per Cent of Possible Sunshine at Washington, D. C., and Albany, N. Y.*

(From U. S. Weather Bureau Records.)

	Washington, D. C. 56-year Average		Albany, N. Y. 50-year Average	
	No. Hours	% of Possible	No. Hours	% of Possible
January	140	46	122	41
February	163	54	152	51
March	208	56	197	53
April	232	58	217	53
May	273	61	259	57
June	280	63	281	61
July	288	64	289	62
August	261	62	263	61
September	230	61	219	58
October	210	61	182	53
November	161	53	113	38
December	138	46	104	37
For year	2584	57	2398	54

* R. E. Falconer.

TABLE 8

Maximum Possible Duration of Sunshine for the Shortest and Longest Days in the Year *

Latitude	December 22 in Hours and Minutes	June 21 in Hours and Minutes
0	12 07	12 07
10	11 32	12 43
20	10 55	13 20
30	10 13	14 05
40	9 19	15 01
50	8 04	16 23
60	5 52	18 52
65	3 34	22 03

* Smithsonian Physical Tables (1933), page 610.

Figure 15 shows the time of sunrise and sunset at various latitudes in the Northern Hemisphere. The duration of sunshine for any day of the year may be obtained from the difference between the time of sunrise and sunset.

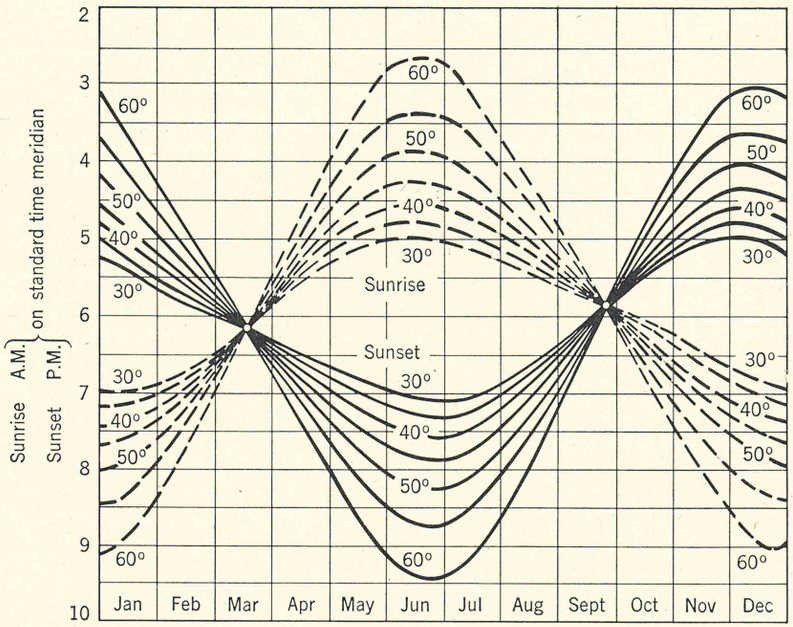

FIG. 15. Time of sunrise and sunset at various latitudes in the northern hemisphere. (F. Benford, *Illum. Eng.*, **42**, 527, 1947.)

EFFECT OF ALTITUDE

The direct solar ultraviolet intensity increases with altitude above sea level, owing to the fact that with increasing elevation the radiation does not have to traverse as thick a layer of atmosphere, so that the absorption is decreased. On the other hand, the scattered ultraviolet radiation from the sky decreases with altitude, since the lower, more turbid, part of the atmosphere is responsible for most of the scattering. The magnitude of these two effects depends upon the degree of turbidity of the atmosphere and on the angular elevation of the sun above the horizon. The rate of increase with height above sea level is greater the more turbid the atmosphere, the less the angle of elevation of the sun above the horizon, and the shorter the wavelength under consideration.

The effect of elevation on the direct solar intensity calculated for two different wavelengths for two values of solar altitude is shown in Fig. 16 for a normally clear atmosphere. For a more turbid atmosphere the curves would be relatively steeper. There is a great scarcity of satisfactory measurements of this kind.

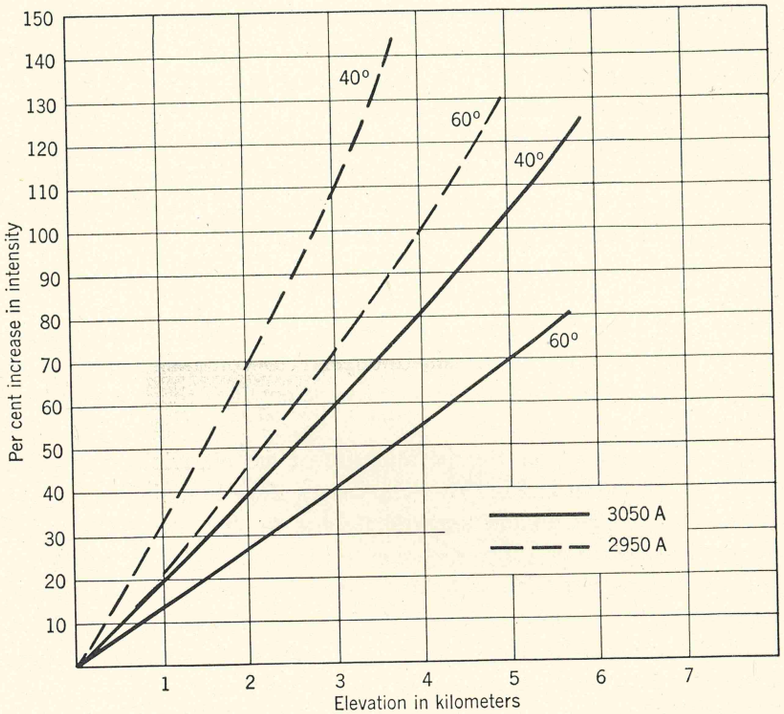

FIG. 16. Effect of elevation above sea level on ultraviolet intensity for different values of solar altitude.

Measurements of the *direct* solar radiation of wavelengths less than 3132 A by Coblentz showed that the intensity on the San Francisco Peaks at 10,500 ft was about 35 per cent higher than that at the Lowell Observatory at an elevation of 7300 ft. This corresponds to an increase of about 35 per cent per km. Measurements of the combined direct and sky radiation (wavelength not specified) on a horizontal surface showed an increase of 15 per cent per km in the Alps.

Although the total amount of energy at high altitudes is significantly

greater than that at sea level, its erythemic effectiveness at high altitudes may be out of all proportion to its intensity as many a mountain climber has discovered to his sorrow. This is because of a change in spectral quality of the radiation. A relatively greater amount of radiation near the short-wave end of the spectrum is present. Changes in the energy distribution near the short-wave end of the spectrum will have a most pronounced effect in producing erythema because it is just in this wavelength region that sunlight is most effective. Energy at 2950 A is about 100 times as effective in producing erythema as energy at 3150 A, i.e., 0.1 μw per cm^2 will produce the same effect as 10 μw per cm^2 at 3150 A. Accordingly, any change in the quality of sunlight which shifts the threshold towards shorter wavelengths will greatly increase its erythemal action. So effects are observed due to amounts of radiation which are very small in comparison with the total ultraviolet.

Ultraviolet Limit of Direct Sunshine

Determination of the limit of ultraviolet in the solar spectrum is very difficult, and the results obtained depend to some extent upon the method used. The shortest measured wavelength at the earth's surface is 2863 A.[12]

The calculated values for the intensity of the ultraviolet end of the spectrum are shown in Fig. 17. The curves show how the shortest observable wavelength in the ultraviolet shifts to shorter wavelengths as the air mass decreases (corresponding to increasing solar elevation).

These values show the shift in the ultraviolet limit towards shorter wavelengths in the summer which accounts for the greater therapeutic effect of summer sunshine. The calculations are in qualitative agreement with the results of numerous other observers.

Utilization of Solar Radiation

Any attempt to make use of solar radiation must involve knowledge of the available hours of sunshine. The duration of sunshine throughout the year at various latitudes is shown in Table 7. Where exposures are to be made through windows it is necessary to know more than the interval between sunrise and sunset; it is necessary to know the duration of sunshine on the plane of the window. Benford and Bock[13] have prepared charts by means of which the time of incidence of sunshine on any vertical plane in the Northern Hemisphere between latitude 30° and 60°, for any orientation of the plane and for any date of the year, may

be determined. Figure 18 shows one of these charts giving the time of incidence of the sun on various vertical planes throughout the year at 45° north latitude. In this figure a plane is designated by the two points at which it cuts the horizon. Thus an east-west plane (north window) would be designated at 90° east of south and 90° west of

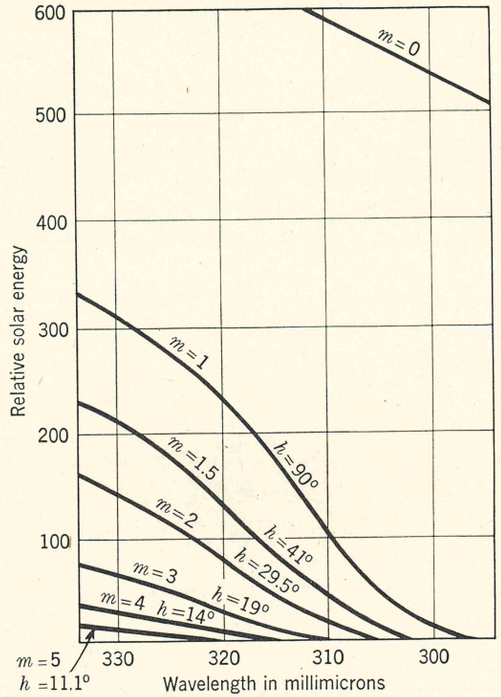

Fig. 17. Calculated values of ultraviolet intensity for different values of air mass. (K. Büttner and E. Sutter, *Strahlentherapie*, **45**, 451, 1932.)

south. From the figure it can be seen that this plane would receive no sunshine on its north side from September to March. Between March and September this plane would receive sunshine on its north side for several hours during the morning and afternoon. This interval reaches a maximum of about 4 hr in June. An east window designated in Fig. 18 as 0° north 0° south receives sunshine from sunrise till noon. In January this would be a little over 4 hr. The use of these curves requires a clear visualization of the particular situation under analysis, in order to distinguish the illuminated side from the shadow side of a plane.

Figure 19 shows the total annual hours of sunshine received on vertical surfaces facing various points on the horizon at several different latitudes.

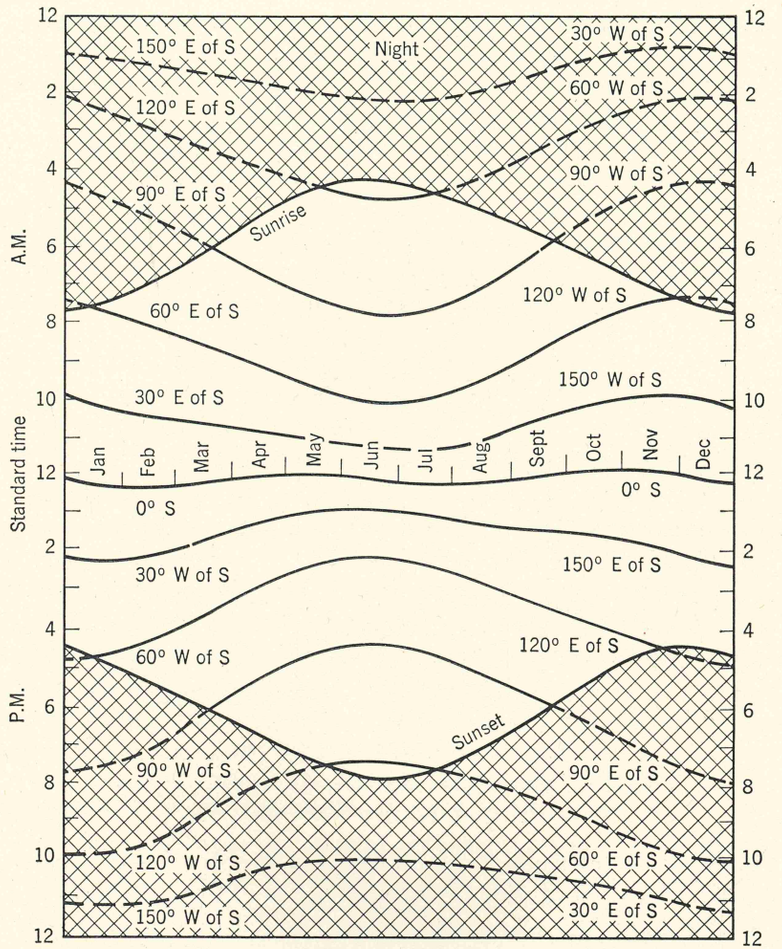

FIG. 18. Chart for determining incidence of sunshine on any vertical plane at 45° north latitude. (F. Benford and J. E. Bock, *Trans. Illum. Eng. Soc.*, **34**, 200, 1939.)

Window frames cause a slight departure from the ideal case and cause a significant loss of possible hours of sunshine. In some instances this amounts to as much as 12–14 per cent of the available hours of sunshine.

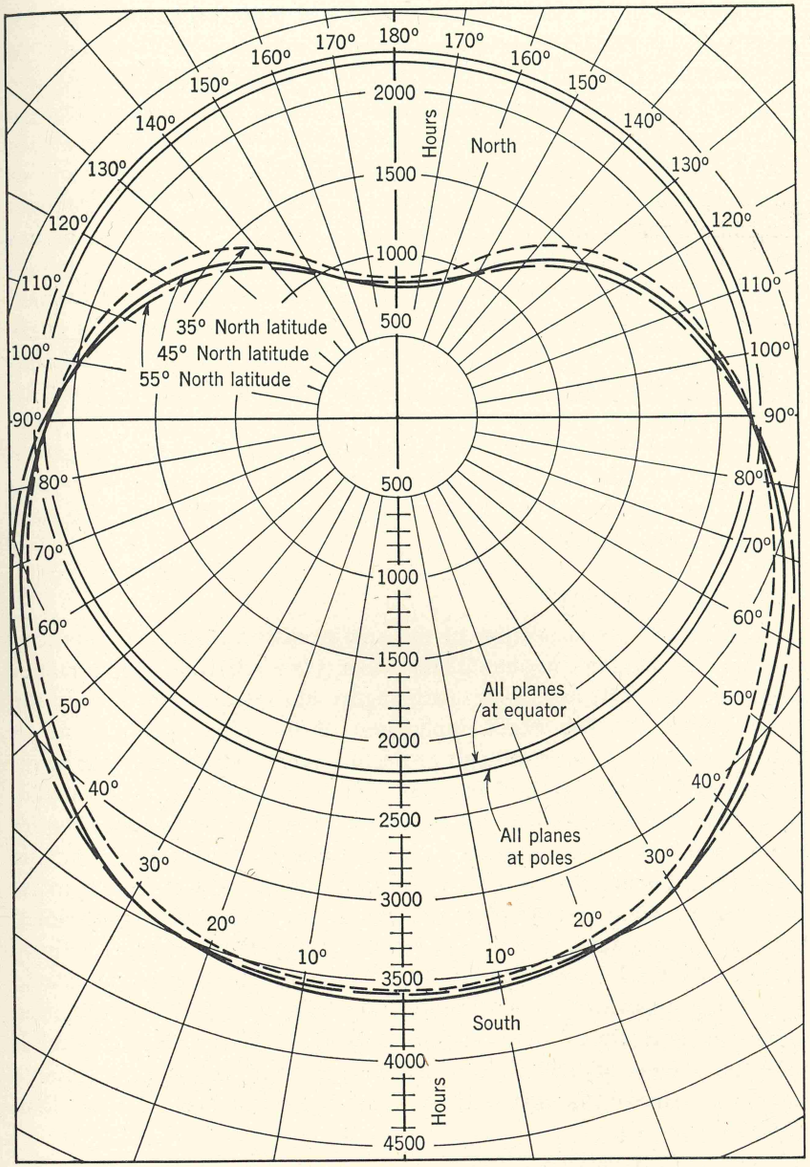

FIG. 19. Total annual hours of sunshine received on vertical surfaces facing various points on the horizon at different latitudes. (F. Benford and J. E. Bock, *Trans. Illum. Eng. Soc.*, **34**, 200, 1939.)

Windows of ultraviolet-transmitting glass have been suggested for therapeutic purposes. Their usefulness, however, is very limited. In north windows they are almost useless. For example, Clark has shown that, in a room with ultraviolet-transmitting glass in a north window in March and April, a child at 5 m from the window would have to sit for 20 hr in order to obtain as much ultraviolet as it would receive out of doors in two min at noon. In windows which receive direct sunlight for some hours of the day they are more effective. However, as has been pointed out on page 119, a large fraction of the ultraviolet comes from the sky so that windows (which ordinarily take in only a small portion of the sky) can rarely admit half as much radiation as is available out of doors in a location exposed to a large portion of the hemisphere. To be really effective ultraviolet-transmitting glass should be used in a solarium which is exposed to a large portion of the hemisphere.

Measurements of the direct solar radiation alone may tend to give a false picture of the radiation "climate" of a place. It is necessary also to take into account sky radiation and hence consider clouds, fog, and all other atmospheric phenomena.

Artificial Sunlight *

It is evident by inspection of the energy distribution of the various sources described in Chapters 2 and 3 that it is a relatively simple matter to match artificially any of the wavelengths and intensities present in the solar spectrum. The exact duplication of the solar spectrum in its entirety presents a more difficult problem. Arcs radiate sufficient ultraviolet but too little infrared in proportion. The solar spectrum could, of course, be duplicated by an incandescent source at the temperature of the sun. But there are no such terrestrial sources. The available incandescent sources have spectra differing from the sun in two respects: first, for the same amount of visible energy they radiate less ultraviolet; second, for the same amount of visible energy they radiate relatively more in the far infrared. Accordingly, sunlight can only be duplicated by adding ultraviolet to and subtracting long-wave infrared radiation from the spectrum of an incandescent body. This is achieved practically by a combination of arcs and incandescent lamps with suitable filters to remove the far infrared and the ultraviolet shorter than $\lambda 2900$ A.

* A detailed description of "An Artificial Sunshine Solarium" is given by G. F. Prideau, *Illum. Eng.*, **12**, 762 (1946).

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5 Transmission

When a parallel beam of radiation passes through an absorbing medium a constant fraction of the radiation is absorbed in each unit distance of the medium traversed. Thus the intensity of the radiation in the medium falls off with increasing thickness according to an exponential relation. This relation, known as Lambert's law, is:

$$I/I_0 = e^{-\alpha t} \tag{1}$$

where I_0 = the intensity of the radiation entering the medium.
I = the intensity of the radiation after traversing a distance t through the medium.
e = the natural logarithmic base.
t = the thickness of the medium traversed in centimeters.
α = absorption coefficient per centimeter.

I/I_0 is called the transmittance factor. The absorption coefficient α is the fraction of the radiation which is absorbed in each unit distance traversed. The absorption coefficient is a characteristic of the material only. The transmittance depends upon the thickness.

In practice we are usually concerned with the amount of radiation which emerges from a substance when a given amount is incident on the front surface. This is called the *transmission* of the material. Part of the incident radiation is reflected at the front surface; part of it is absorbed in passing through the substance; and part is reflected at the back surface. In the case of glass about 4 per cent of the radiation is reflected at each glass air surface (when the radiation is incident normal to the surface). Lambert's law does not take into account this reflection loss but is only concerned with the absorption loss within the medium. For this reason the *transmittance* is greater than the *transmission* (by about 8 per cent for glass in air). Thus 4 per cent of an incident beam is reflected at the front surface of a piece of glass so that only 96 per cent

actually enters the glass. Another 4 per cent is reflected at the surface where the light emerges, so that even if the glass had no absorption (and consequently 100 per cent transmittance) its transmission would only be 92 per cent.

If we let I_0 represent the intensity of the radiation incident on the first surface and let I represent the intensity of the radiation emerging from the second surface and thus take account of the reflection losses, equation 1 is written

$$I/I_0 = (1 - R)^2\, e^{-\alpha t} \tag{2}$$

where I/I_0 = transmission.
R = reflection coefficient.
α = absorption coefficient per centimeter.
t = thickness of the substance in centimeters.

The distinction between transmittance and transmission is not always made, and the term transmission is often loosely used; sometimes it means transmittance and sometimes transmission.

The absorption coefficient is a function of wavelength. In general, solids and liquids show rather broad absorption and transmission bands, whereas gases and vapors may show sharp discontinuities in their transmission. Most common materials are more likely to be good absorbers than good transmitters of ultraviolet radiation.

A convenient way of presenting information about the ultraviolet transmittance of substances is to give the values of the absorption coefficient at various wavelengths. Knowing this, the transmittance for any particular thickness may be calculated from Lambert's law (equation 1). For convenience in calculating, this relation is given graphically in Fig. 1 where values of transmittance are plotted as a function of α with the thickness of the absorbing medium as a parameter. Figure 2 shows the values of transmittance as a function of the thickness of the medium with absorption coefficient as a parameter.

Essentially the same information is presented in Fig. 3 which shows a plot of the transmittance as a function of the product αt. Because of the exponential nature of Lambert's law, the transmittance changes much more rapidly with change in α or t for large values of the product αt than for small values. Thus, for example, it can be seen from Fig. 3 that when $\alpha = 1$ an increase in thickness from 1 to 2 cm which would increase the product αt from 1 to 2 would only decrease the transmittance from 0.35 to 0.14. However, for $\alpha = 3$ the same change in thickness would decrease the transmittance from 0.05 to 0.0025. In the first case, the transmittance decreases about fourfold and in the second case

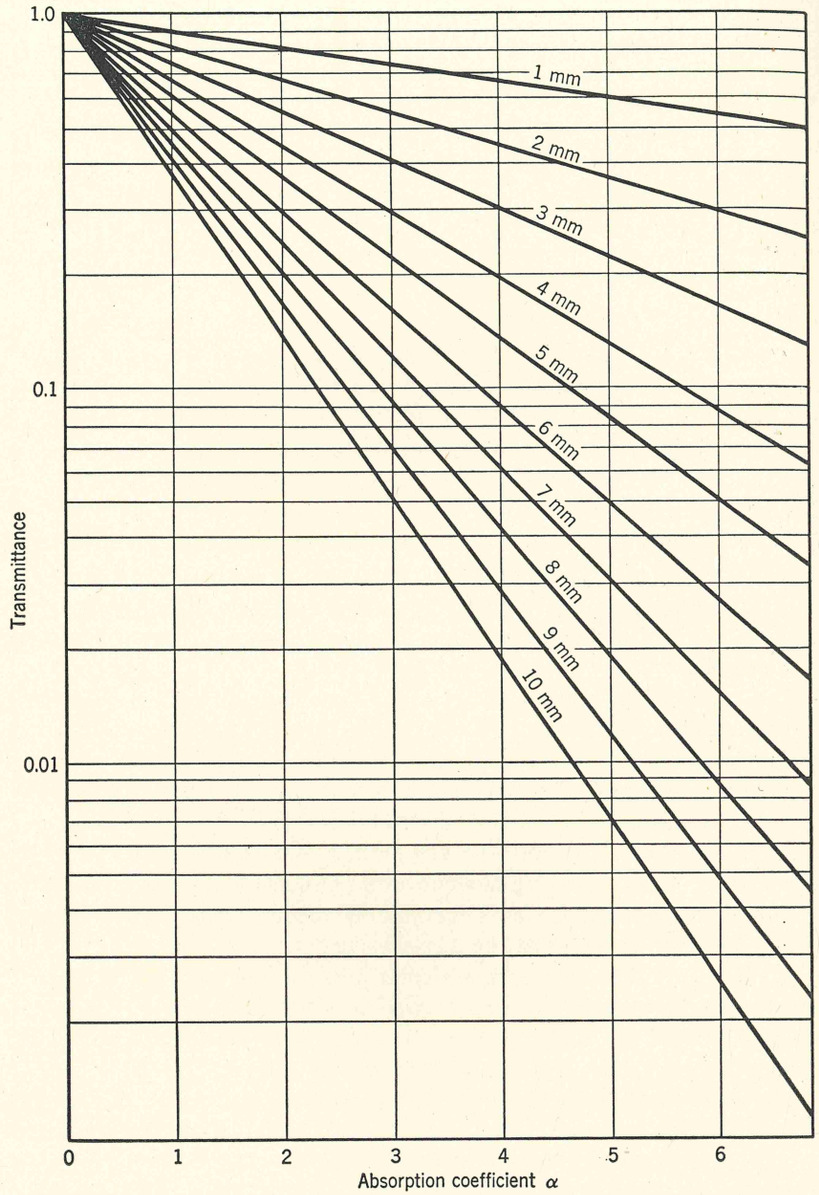

FIG. 1. Transmittance as a function of absorption coefficient for various thicknesses of absorbing medium.

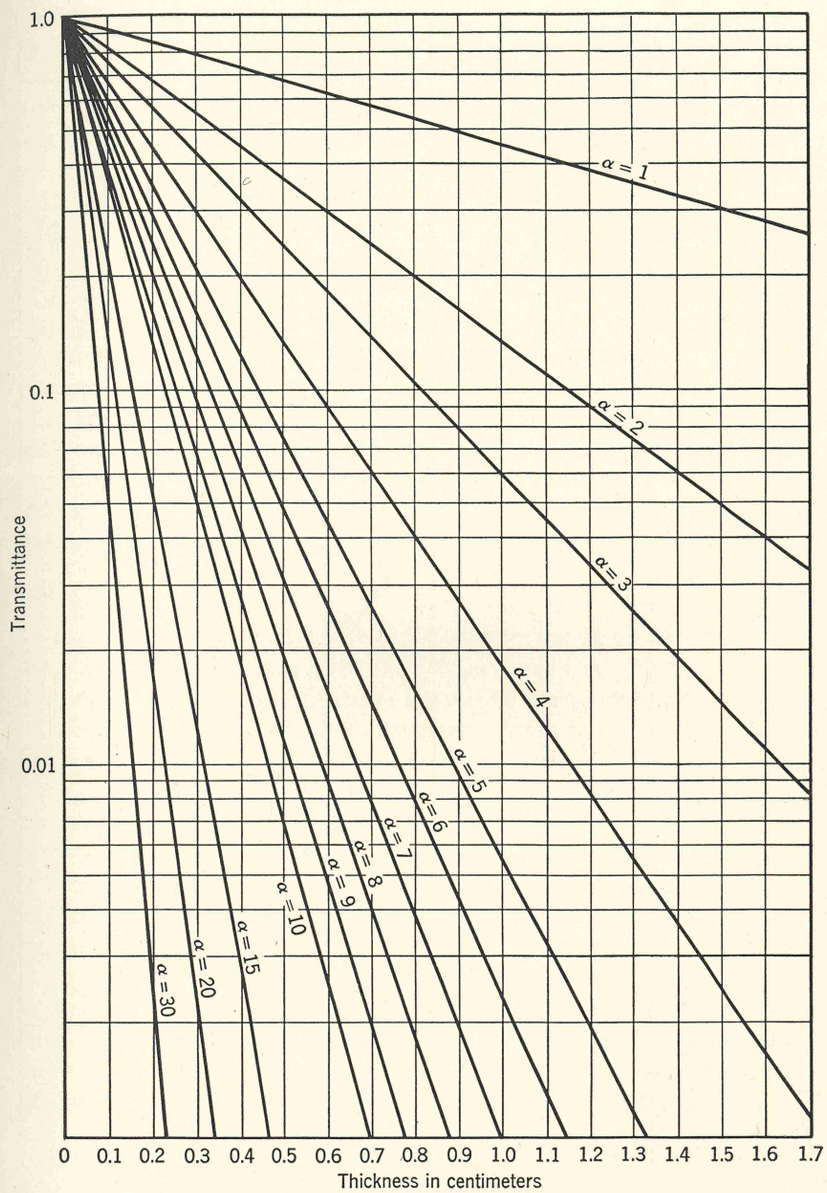

FIG. 2. Transmittance as a function of thickness for various values of absorption coefficient.

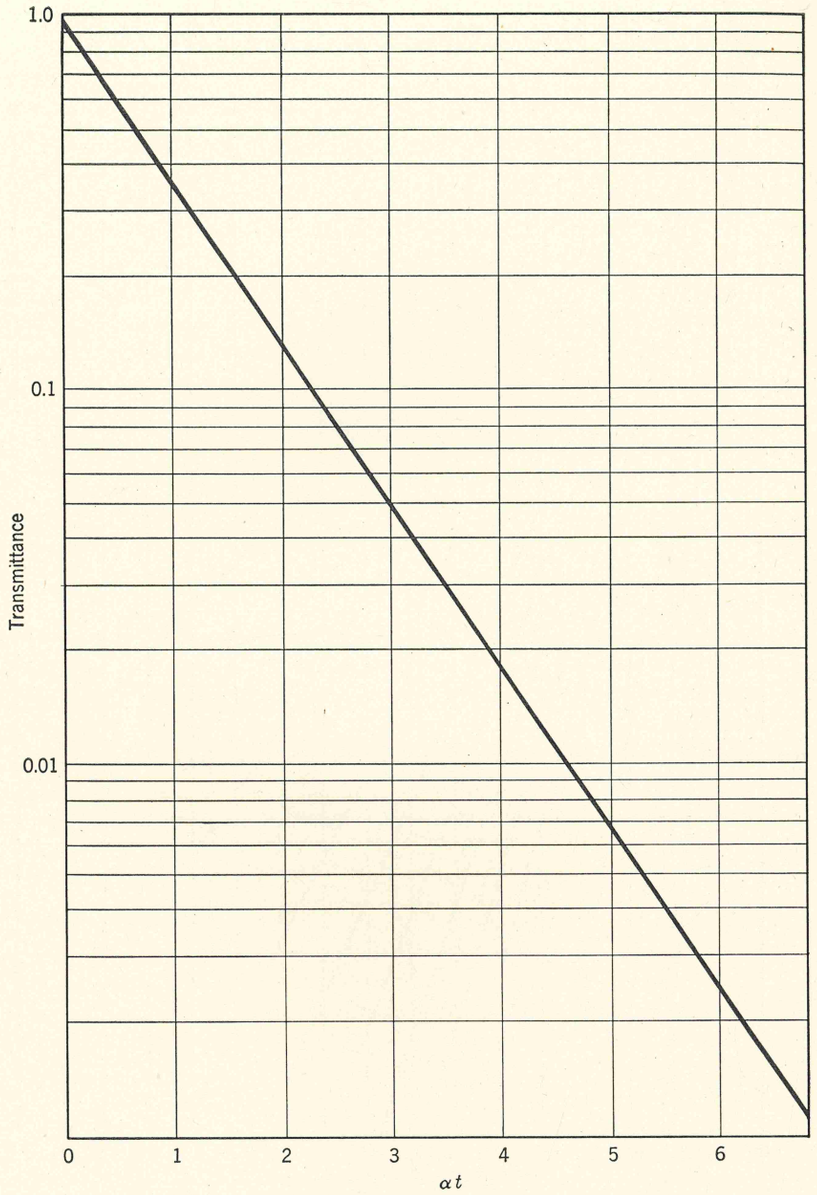

FIG. 3. Transmittance as a function of αt.

twentyfold. Similarly the change in transmittance with a change in α is small for a thin layer of material but large for a thick layer.

The practical significance of this is that small differences in the thickness of a highly transparent material have a relatively small effect on the transmittance and similarly small differences in the absorption coefficient have a relatively small effect on the transmittance of an extremely thin layer of an absorbing medium. On the other hand, where the value of αt is large a small change in either thickness or absorption coefficient produces a large change in the transmittance.

It is not within the scope of this book to discuss the fundamental nature of the absorption process but rather to present data on the absorption of various commonly used materials. Accordingly, it is convenient to classify these materials with a view to their application rather than to their constitution. A useful classification of this kind is: materials suitable for lamp bulbs and containers, materials suitable for filters for isolating various spectral regions, other materials of interest in science or technology. Obviously, these classes are arbitrary and overlapping but nevertheless convenient for discussion.

GLASS

The materials most widely used for lamp bulbs which are required to transmit ultraviolet are quartz and various forms of glass. Ultraviolet transmission is only one of many properties which must be considered in the choice of a suitable bulb material. Some of the other properties are mechanical strength, resistance to thermal shock, thermal expansion, ability to seal to other glasses and metals, resistance to weathering, chemical stability, surface tension, viscosity, melting point, and, of course, cost. Both the physical and chemical properties of glass show a wide range, depending upon its chemical constitution. The choice of a particular glass usually represents a compromise among these various properties.

The transmission of glass for ultraviolet is largely determined by the content of iron oxide which absorbs strongly in this region. Even small amounts present as impurities to the extent of less than 0.01 per cent may have profound effects.[1] Low transmission in the ultraviolet is usually attributed to the presence of the iron in the ferric condition.

WINDOW GLASS

Ordinary window glass in thicknesses of 1 mm or more is practically opaque to ultraviolet of wavelengths shorter than 3000 A. A common thickness for home windows is $\frac{1}{8}$ in. Thus an ordinary window pane,

although it admits most of the incident visible radiation excludes practically all the wavelengths of the tanning and therapeutic ranges.

TABLE 1

ABSORPTION COEFFICIENT OF WINDOW GLASS *

Wavelength in Angstroms	α cm^{-1}
3150	7.6
3200	5.0
3400	1.29
3600	0.45

* Calculated from W. W. Coblentz and R. Stair, *J. Research Natl. Bur. Standards*, **3**, 629 (1929).

Values of the absorption coefficient for window glass are given in Table 1. Figure 4 shows the per cent of transmission as a function of wavelength for three thicknesses of window glass. As can be seen from the curve the transmission falls off very rapidly with wavelength below 3600 A.

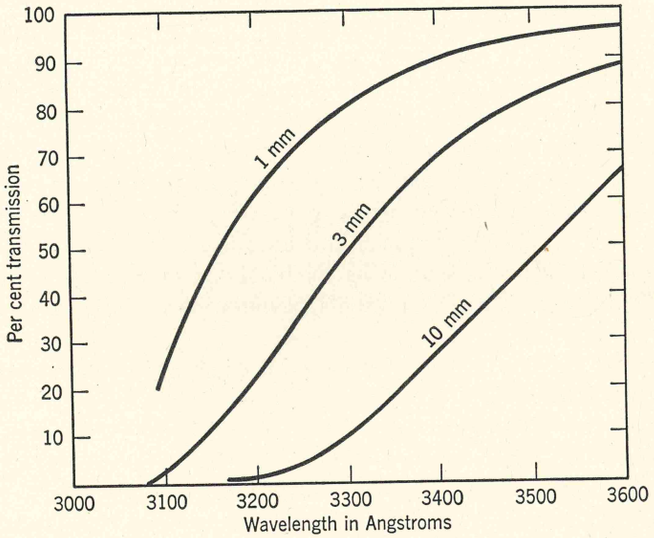

FIG. 4. Transmission for various thicknesses of window glass.

Window glass ⅛ in. in thickness is sufficient protection for the eyes and skin against the ultraviolet radiation from ordinary ultraviolet

sources. In the case of extremely intense sources of ultraviolet and high intensities of visible and infrared radiation it may not be adequate.

PYREX

The heat-resistant, chemically resistant Pyrex * glasses transmit significantly more ultraviolet than window glass. As can be seen from Fig. 5, a 1-mm thickness of No. 774 chemical Pyrex transmits about

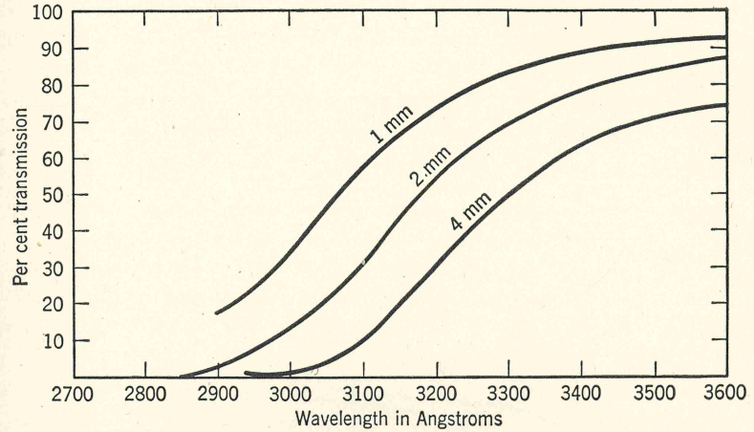

FIG. 5. Transmission for various thicknesses of Pyrex clear chemical glass No. 774.

35 per cent at 3000 A. Like most other clear glasses, the transmission increases rapidly with increasing wavelength up to about 2 μ in the infrared where the transmission begins to decrease.

COREX

Another heat-resistant glass with a higher ultraviolet transmission than Pyrex is Corex D No. 9700. The transmission curve for this glass is shown in Fig. 6. As can be seen from the figure, the transmission of this glass is high at 3000 A and is very small at wavelengths shorter than 2500 A. For this reason it is useful as a bulb for sunlamps, as it transmits the therapeutic and tanning radiation while cutting off the shorter wavelengths. This is particularly advantageous for mercury vapor sunlamps, as it transmits the desired radiation in the 3000 A region but in thicknesses of 1 mm or more completely filters out the unwanted strong 2537 A line of mercury.

* "Pyrex" is not the name of a material, but is a trademark of the Corning Glass Works covering various thermally, electrically, or chemically resistant glasses of different compositions.

Glasses Transmitting in the Far Ultraviolet

A number of other glasses have been developed which transmit still farther in the ultraviolet than chemical Pyrex and Corex. One of them is Pyrex No. 9741 which was developed especially for bactericidal lamps. This glass has a transmission which ranges from 40 per cent to 70 per cent at 2537 A for a 1-mm thickness. It has a small transmission at 1849 A. It is manufactured to three specifications requiring a small controlled transmission in this region. These values together with the corresponding transmission at 2537 A are given in the accompanying table.

Transmission of 1 mm of Pyrex Brand Glass No. 9741

At 1849 A, Per Cent	At 2537 A, Per Cent
Less than 0.25	40
0.5–4.0	60
Greater than 5.0	70

Figure 6 shows the transmission of the last type listed in the table.

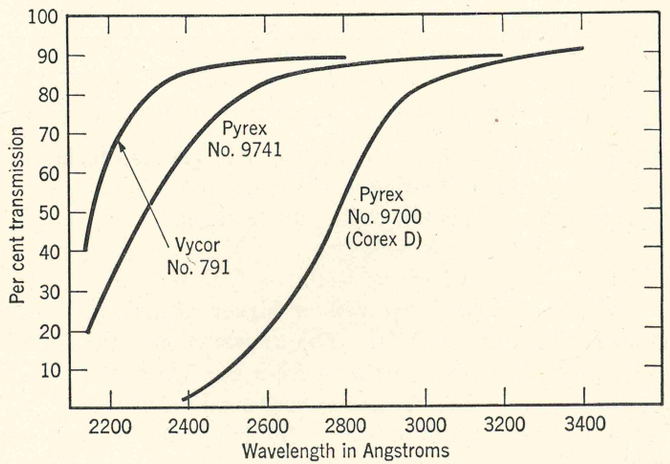

Fig. 6. Transmission of 1 mm thickness of Pyrex and Vycor glasses. (M. E. Nordberg, *J. Am. Ceram. Soc.*, **30**, 184, 1947.)

Vycor *

A group of glasses which approach silica in their properties are called Vycor glass. These are made by a process which involves leaching the fluxes from an alkali borosilicate glass and firing the residual high-silica, porous structure at about 1200°C to consolidate it.[2] The treatment shrinks the porous structure to 65 per cent of its original volume. This process makes the extremely high temperatures which are required for quartz unnecessary and makes possible fabrication of a large number of shapes which could not be made from such a high-melting glass in any other practicable way.

* A trademark of the Corning Glass Co. registered at U. S. Patent Office.

Vycor No. 790 has a high transmission at 3650 A but falls to 0–10 per cent for a 2-mm thickness at 2540 A. Vycor No. 791 has physical properties identical with No. 790 except a higher transmission for ultraviolet. The transmission for Vycor No. 791 in 1-mm thickness is shown in Fig. 6. Its transmission is about 85 per cent at 2537 A and practically 0 at 1849 A (not corrected for reflection losses).

Quartz

Quartz is used for transmission farther in the ultraviolet than can be obtained with glass or where a substance is required which can withstand higher temperatures than glass. Both fused and crystalline quartz

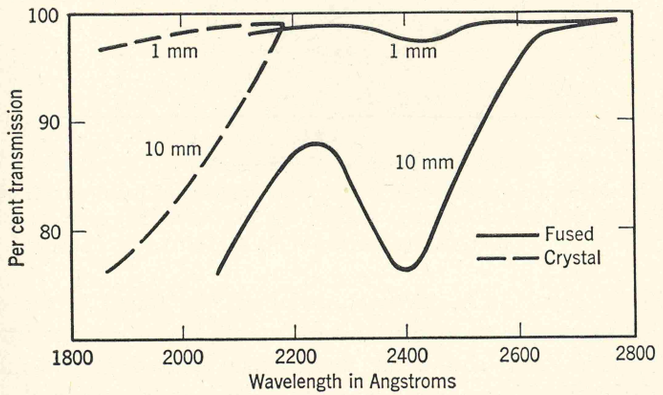

Fig. 7. Transmission for crystal and fused quartz. (A. Schraub, *Physik. Z.*, **43**, 64, 1942; T. Lyman, *Spectroscopy of the Extreme Ultraviolet*, Longmans, Green and Co., New York.)

have a high transmission for visible and ultraviolet down to wavelengths of about 2000 A. Below this the crystalline quartz has a considerably higher transmission than the fused material. The transmission for crystal and fused quartz is shown in Fig. 7. Except for optical instruments in the far ultraviolet fused quartz is adequate for most purposes.

Different samples of fused quartz vary considerably in transmission. Figure 8 shows the limits of the transmission of a number of samples obtained from two different manufacturers.

Transmission measurement by E. A. Taft [3] shows that many commercial samples of fused quartz are very inhomogeneous. These inhomogeneities cannot be detected in the visible range and are rather small

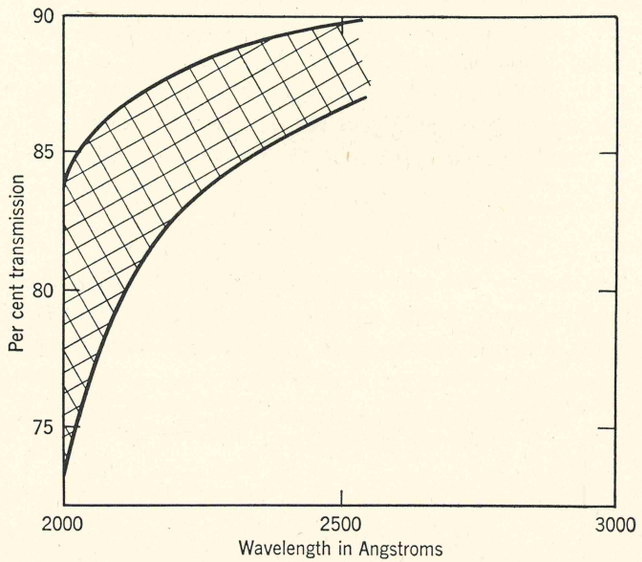

FIG. 8. Limits of the transmission of thirty-one samples of fused quartz obtained from two different manufacturers. Samples 1/16 in. thick. No correction for reflection. (Courtesy of E. A. Taft.)

at 2537 A. At 2138 A, however, striations are found in the quartz which are practically opaque to this radiation. These are illustrated in Fig. 9. This figure shows the fluorescence excited in willemite by 2138 A radiation after passing through a piece of apparently clear material. The dark portions are shadows cast by the relatively opaque regions of the quartz. The maximum values of transmission found by Zernike [4] at 1990 A and 1862 A for a 1-cm thickness of quartz were 75 per cent and 60 per cent, respectively.

CALCITE, FLUORITE, AND ROCK SALT

Three materials in addition to quartz which are used to a considerable extent as lenses and prisms in optical instruments for the ultraviolet are

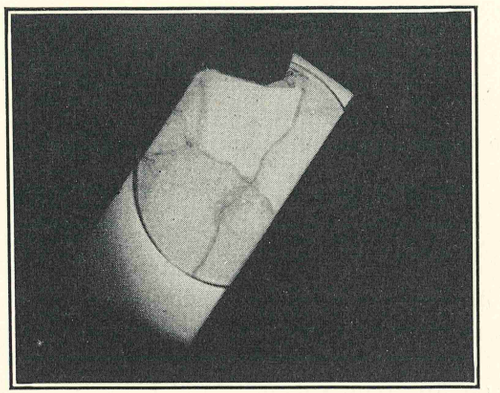

FIG. 9. Fluorescence excited in willemite by 2138 A radiation after passing through fused quartz. The dark portions represent opacities in the quartz. (Courtesy of E. A. Taft.)

calcite ($CaCO_3$), fluorite (CaF_2) and rock salt (NaCl). The absorption coefficients of these materials at various wavelengths and the thickness which has a transmission of 50 per cent are given in Table 2.

TABLE 2

TRANSMISSION OF CALCITE, FLUORITE, AND ROCK SALT

Substance	Wavelength in Angstroms	Absorption Coefficient α	Thickness for 50% Transmission, cm
Fluorite	1860	0.22 *	3.15
Calcite	2150	3.36 *	0.21
	2300	1.25	0.56
	2400	0.58	1.20
	2500	0.40	1.73
	2600	0.29	2.39
	2700	0.20	3.46
	2800	0.16	4.33
Rock salt	1860	0.36 *	1.93
	2100	0.26	2.67
	2310	0.15	4.62
	2800	0.046	15.1

* *International Critical Tables*, Vol. V, McGraw-Hill Book Co., New York, 1929.

Commercial Glass Filters

All the materials discussed so far show the common characteristic of clear glasses of cutting off radiation shorter than some critical wavelength but passing all longer wavelength radiation until far out in the infrared. A number of glasses are available, however, which have a cut-off on the long-wave side as well. For the most part these do not have suitable characteristics for lamp bulbs, but they are used extensively as filters. Transmission curves for several of these commercial glasses are shown in Fig. 10. Most of them transmit a little radiation in the blue or violet and also in the red (not shown in Fig. 10) and hence have a deep purple color. In general, their transmission is lower than that of the clear glasses. They are particularly useful in connection with lamps for exciting fluorescence.

No. 5860 transmits no visible radiation and hence is useful for the study of feebly fluorescent substances which are excited in the range around 3600 A. No. 5840 transmits no visible violet and very little red and has a higher transmission at 3600 A, but it also transmits considerably more shorter wavelength radiation. No. 5874 has practically the same transmission in the ultraviolet as No. 5840 but transmits slightly in the violet. It is a heat-resisting glass, however, and may be used close to intense sources. No. 5970 has a slightly broader transmission band than No. 5874. No. 9863 transmits practically the entire ultraviolet region down to 2300 A and only a trace of red and violet. It is not resistant to heat shock, however, and is slightly attacked by moisture. It is also subject to solarization.

The above-mentioned glasses by no means constitute a complete list of the available ones. They do, however, indicate the range of transmission which can be covered by glass. Table 3 gives the transmission factors of a number of other glasses of American and foreign manufacture.

Solarization

Although glass is a relatively stable material it does undergo some chemical changes in the course of time. This is noticeable in a decrease in its ultraviolet transmission. Exposure to sunlight causes a photochemical reaction which results in a decrease in ultraviolet transmission. This decreased transmission caused by exposure to sunlight is called solarization. The term is now also applied to the effect produced by artificial sources of ultraviolet as well. The magnitude of the effect depends upon the kind of glass, the temperature, the time, the wave-

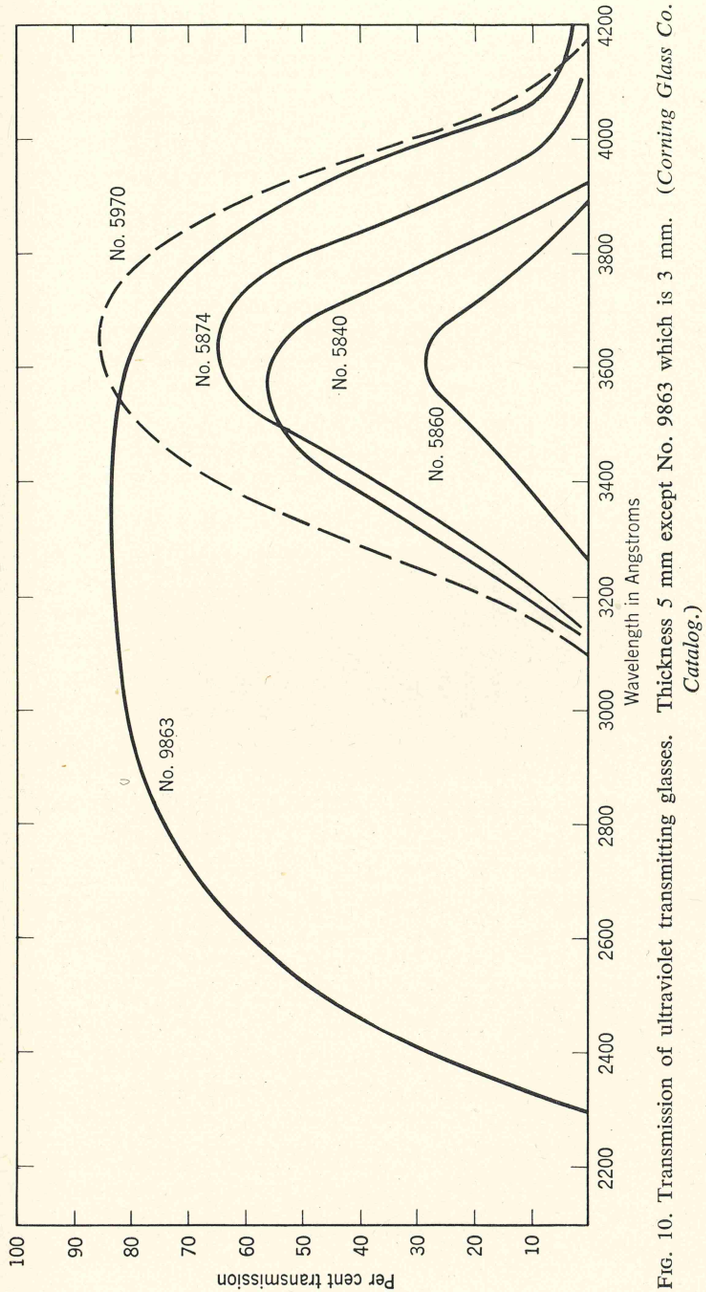

Fig. 10. Transmission of ultraviolet transmitting glasses. Thickness 5 mm except No. 9863 which is 3 mm. (*Corning Glass Co. Catalog.*)

TABLE 3 *

TRANSMISSION OF COLORED GLASSES OF AMERICAN AND FOREIGN MANUFACTURE

Wavelength in Angstroms	AO Crown 1.50 Neut 1.68 mm	BL Crookes 1 Neut 2 mm	BL Crookes 2 Neut 2 mm	BL Crookes 3 Neut 2 mm	BL Smoke A Neut 2 mm	BL Smoke B Neut 2 mm	BL Smoke C Neut 2 mm	CG 396 Green 2 mm	CG 428 Bl-grn 2 mm	CG 556 Sig blue 100% 5 mm
2200		†	†	†	†	†	†			
2400										
2600										
2800	0									
3000	0.10					0		0	0	
3200	0.56				0	00		0.020	0.004	0
3400	0.83	0	0	0	0.44	0.14	0	0.280	0.266	0.060
3600	0.89	0.06	0.22	0.20	0.83	0.60	0.32	0.530	0.652	0.370
3800	0.91	0.72	0.70	0.65	0.89	0.74	0.61	0.670	0.780	0.650
4000	0.92	0.86	0.80	0.74	0.90	0.76	0.64	0.735	0.830	0.780
5000	0.92	0.95	0.83	0.55	0.85	0.59	0.35	0.820	0.835	0.205
6000	0.92	0.99	0.85	0.58	0.85	0.59	0.32	0.720	0.253	0.0008
7000		0.99	0.97	0.90	0.95	0.88	0.75	0.430	0.040	0.0008

TABLE *3a*

Wavelength in Angstroms	BL Blue O Blue 2 mm †	BL Blue A Blue 2 mm †	BL Blue B Blue 2 mm †	BL Blue C Blue 2 mm †	CG 557 Lt Purp 6.2 mm	CG 555 Purp 4.8 mm	CG 507 Purp 3 mm	CG G985B Green	CG G985B Blue	CG 585 Bl-Purp Tr UV 1 mm	CG 597 Red-Purp Tr UV 1 mm	CG 587 Rd-Purp Tr UV 2 mm
2200									0			
2400								0	0.02			
2600								0.38	0.18			
2800								0.34	0.46	0	0	0
3000	0.020	0.11	0.08	0.11				0.12	0.68	0.153	0.116	0.039
3200	0.45	0.68	0.65	0.60				0.36	0.78	0.650	0.570	0.342
3400	0.79	0.88	0.87	0.87			0.212	0.73	0.84	0.860	0.850	0.640
3600	0.88	0.94	0.93	0.97			0.552	0.79	0.86	0.910	0.913	0.795
3800	0.94	0.97	0.96	0.98	0.795	0.783	0.728	0.75	0.86	0.925	0.890	0.700
4000	0.98	0.98	0.97	0.98	0.861	0.845	0.726	0.45	0.81	0.900	0.714	0.265
5000	0.99	0.94	0.83	0.66	0.497	0.1015	0.028			0.199	0.026	000
6000	0.96	0.86	0.62	0.37	0.095	0.0002	0.10			0.014	0.065	0.000
7000	0.98	0.97	0.93	0.81	0.360	0.035	0.230			0.505	0.505	0.255

* *Handbook of Chemistry and Physics*, Chemical Rubber Publishing Co., Cleveland, Ohio, 30th Edition, 1948.
† Corrected for reflection.

TABLE 3*b*

Wavelength in Angstroms	CG 584 Red Tr UV 1 mm	CG 774 Neut Pyrex 2 mm	CG 970 Neut Corex D 2 mm	CG 980 Neut Corex A 2 mm	CG Rd-Purp Corex A 3 mm
2200			0	0.0115	
2400			0.0027	0.237	0
2600			0.039	0.531	0.135
2800		0	0.305	0.753	0.412
3000	0.129	0.120	0.700	0.846	0.625
3200	0.555	0.610	0.860	0.879	0.793
3400	0.791	0.830	0.902	0.884	0.814
3600	0.830	0.900		0.885	0.797
3800	0.714	0.913			0.430
4000	0.115	0.913		0.887	0.075
5000					000
6000		0.919		0.900	0.001
7000	0.290	0.919			0.231

length, and intensity of exposure. In general, unfiltered radiation from artificial ultraviolet sources causes a greater degree of solarization than natural sunlight. The effect is small in fused quartz but is considerably larger for other glasses.

The change in transmission on solarization for Vycor No. 791 and Pyrex No. 9741 is shown in Fig. 11. Curves *a* and *b* show the transmission of Vycor No. 791 initially and after 230 hours of exposure to a Hanovia 500S quartz arc at a distance of 6 in., respectively. Similarly, curves *c* and *d* are for Pyrex No. 9741 and show the transmission for this glass initially and after exposure under the same conditions. The solarization of the Vycor is almost negligible, whereas that of the Pyrex No. 9741 is very marked.

Solarization takes place relatively rapidly at first, and the rate decreases as the exposure is prolonged. This is illustrated in Table 4 which gives the per cent of decrease in transmission with time for Vycor, Pyrex, and fused quartz when exposed to ultraviolet from a Hanovia arc.

Coblentz studied the solarization of various ultraviolet-transmitting window glasses when exposed to the sun in Washington, D. C., for periods of several hundred days. The transmission to wavelength 3020 A showed a significant decrease in almost all cases and for some glasses was as high as 50 per cent.

The photochemical process of solarization can be reversed by heat

TABLE 3*c*

Jena Glasses

Wavelength in Angstroms	UG 1 Dk Viol Tr UV 1 mm	UG 2 Dk Viol Tr UV 1 mm	UG 3 Violet 1 mm	UG 4 Dk Viol 1 mm	BG 1 Blue Tr UV 1 mm	BG 2 Blue Tr UV 1 mm
2810		0.01			0.04	
3020	0.17	0.27		0.09	0.40	0.04
3120	0.37	0.50	0.04	0.22	0.64	0.16
3340	0.69	0.80	0.55	0.59	0.93	0.63
3360	0.85	0.84	0.91	0.77	0.97	0.84
4050	0.08	0.02	0.85	0.07	0.97	0.70
5090			0.12	0.01	0.14	
6440			0.35		0.01	
7000	0.01	0.12	0.46	0.21	0.51	0.32

Wavelength in Angstroms	BG 3 Blue Tr UV 1 mm	BG 9 Blue-Green 1 mm	BG 10 Blue-Green 1 mm	BG 11 Lt-Blue (Nd) 1 mm	BG 12 Blue Abs Red 1 mm
2810	0.13			0.02	
3020	0.60			0.21	
3120	0.77	0.01		0.38	0.02
3340	0.92	0.21	0.12	0.80	0.39
3360	0.96	0.67	0.60	0.95	0.75
4050	0.86	0.90	0.78	0.97	0.86
5090		0.96	0.88	0.95	0.12
6440		0.86	0.74	1.0	
7000	0.06	0.74	0.63	0.99	0.04

Wavelength in Angstroms	BG 14 Bright Blue 1 mm	BG 17 Col Abs Ht 1 mm	CG 1 Col Abs UV 1 mm	RG 6 Blood Color 1 mm	NG 2 Med Dk Neut 0.1 mm
2810					0.05
3020		0.03	0.02	0.12	0.30
3120	0.13	0.11	0.13	0.20	0.36
3340	0.71	0.46	0.47	0.34	0.46
3660	0.92	0.89	0.86	0.44	0.47
4050	0.98	0.97	0.98	0.49	0.45
5090	0.96	0.98	1.0	0.31	0.52
6440	0.46	0.97	1.0	0.93	0.62
7000	0.30	0.93	1.0	0.98	0.77

BL = Bausch and Lomb Optical Company.
CG = Corning Glass Works.
abs = absorbing.
bl = blue.
dk = dark.
grn = green.
ht = heat.
lt = light.
neut = neutral.
purp = purple.
rd = red.
sig = signal.
tr = transmitting.
UV = ultraviolet.
viol = violet.

TABLE 4

SOLARIZATION OF ULTRAVIOLET TRANSMITTING GLASSES ON EXPOSURE TO QUARTZ MERCURY ARC *

Exposure in Hours	Per Cent Decrease in Transmission at 2537 A		
	Vycor No. 791	Pyrex No. 9741	Fused Silica
0	0	0	0.0
1	1	15	0.1
7	1.5	26	0.7
31	1.5	30	0.9
130	2.0	31.5	1.0
230	2.5	32.5	1.1

* M. E. Nordberg, *J. Am. Ceram. Soc.*, **30**, 174 (1947).

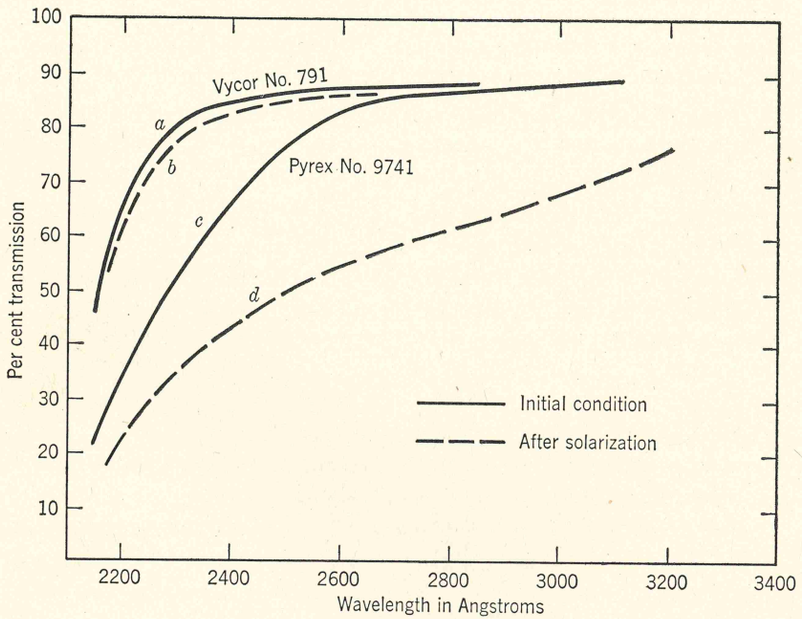

FIG. 11. Effect of solarization on Vycor and Pyrex glasses. (M. E. Nordberg, *J. Am. Ceram. Soc.*, **30**, 174, 1947.)

treatment and the transmission restored to practically its original condition.

Data are not available on the degree of solarization of all types of glass, and for most types the effect is not large in the near ultraviolet. It is a factor, however, which should be taken into account in experiments.

When ultraviolet-transmitting glass is used as the envelope for a mercury arc, another type of deterioration takes place in addition to solarization. This is the formation of a dark layer on the surface of the glass as a result of a reaction with the mercury. In one case studied by Nordberg, this effect in a low-pressure cold-cathode mercury lamp operated for 2000 hr caused a decrease of 13 per cent in transmission of a sample of Vycor No. 791 glass at 2537 A. As a combined result of solarization and mercury blackening, mercury arcs in Pyrex show a very much greater deterioration than similar lamps in Vycor. Other factors such as cathode failure, sputtering, and chemical reactions also have a bearing on the deterioration of lamps.

SHORT-WAVE CUT-OFF FILTERS

Various organic liquids may be used as short-wave cut-off filters in the ultraviolet. By varying the concentration the cut-off may be altered. The accompanying table taken from Bass [5] shows the cut-off wavelength for various concentrations of seven organic substances dissolved in octane. The cut-off is determined by extrapolating the linear portion of the curve to 0 transmission. The cut-off for benzene which is typical, is relatively sharp and shifts to longer wavelengths as the concentration is increased, as can be seen from Fig. 12. The cut-off is much sharper and the curve considerably steeper than is usually the case for glass. The thiophene filter is relatively unstable and must be changed every 20 to 30 min.

INORGANIC SALTS

Solutions of nickelous and cobaltous sulfate have fairly high transmission in the ultraviolet between 2300 and 3300 A and 2300 and 4000 A, respectively, as is shown in curves *a* and *b* of Fig. 13. The nickelous sulfate has high transmission peaks at 5000 A in the visible and at 9000 A in the infrared. The cobaltous sulfate, on the other hand, absorbs strongly in these regions. The result is that a combination of these two, as shown in Fig. 14, transmits approximately 50 per cent of the incident radiation between 2400 A and 3200 A and no other

TABLE 5

SHORT-WAVE CUT-OFF FILTERS

Compound	Concentration, Grams/Liter in Isooctane	Cut-Off Wavelength in Angstroms
Benzene	1.0	2615 *
	9.1	2630
	100	2700
	Undiluted	2800
Chlorobenzene	10	2750
	100	2810
	Undiluted	2875
Cumene	1.0	2670 *
	10	2700
	100	2750
	Undiluted	2920 *
Dehydropyran	0.2	2240 *
	1.0	2310
	10	2540 *
Mesitylene	1.0	2735 *
	10.0	2800
	100	2835
	Undiluted	2900
Phenol	1.0	2800 *
	10	2845 *
Thiophene	1.0	2480
	10	2540
	100	2590

* Extrapolated.

radiation up to 10,000 A except for a 1.5 per cent hump at 5700 A. This solution is quite stable on exposure to ultraviolet.

Cupric sulfate, as is shown in Fig. 15, has a high transmission in the visible and near ultraviolet and absorbs the infrared completely.

By means of these filters to isolate broad regions, in combination with various organic substances, it is possible to construct a set of band-pass filters for the region 2400–3800 A. These filters have a maximum transmission of 30 per cent on the average and transmit over a band having a half-width of 200 A (i.e., at 100 A on either side of the wavelength of maximum transmission their transmission is 50 per cent of the maximum). They are formed by means of a 5-cm quartz cell containing the inorganic solution, a glass filter, and a 1-cm quartz cell contain-

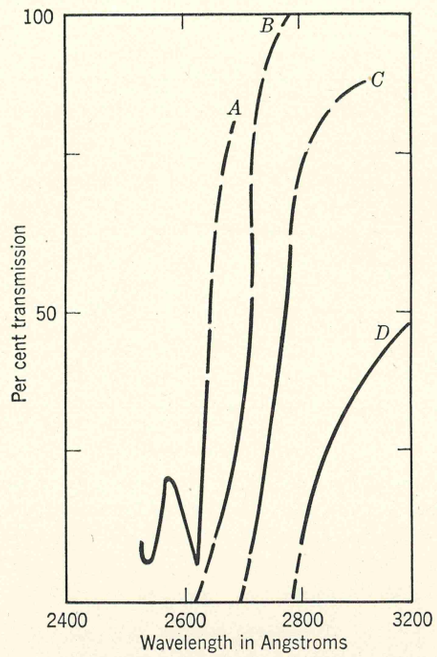

FIG. 12. Transmission of filters of various concentrations of benzene dissolved in octane. *A*. 1.0 grams per liter. *B*. 9.1 grams per liter. *C*. 100 grams per liter. *D*. Undiluted. (A. N. Bass, *J. Optical Soc. Am.*, **38**, 977, 1948.)

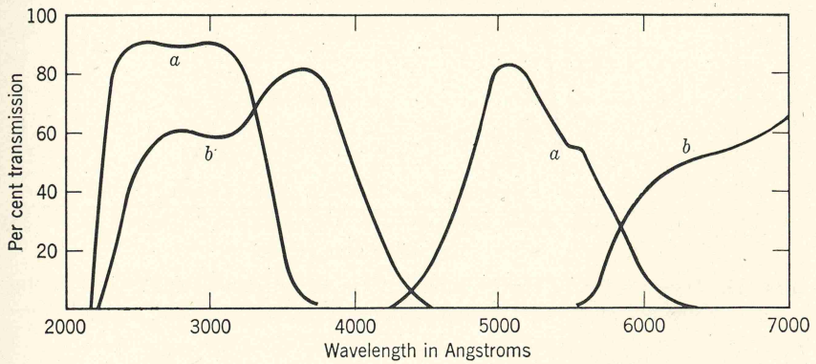

FIG. 13. Transmission of solutions of nickelous and cobaltous sulfate. *a*. 1 cm of $NiSO_4 \cdot 6H_2O$, 500 grams per liter. *b*. 1 cm of $CoSO_4 \cdot 7H_2O$, 300 grams per liter. (M. Kasha, *J. Optical Soc. Am.*, **38**, 929, 1948.)

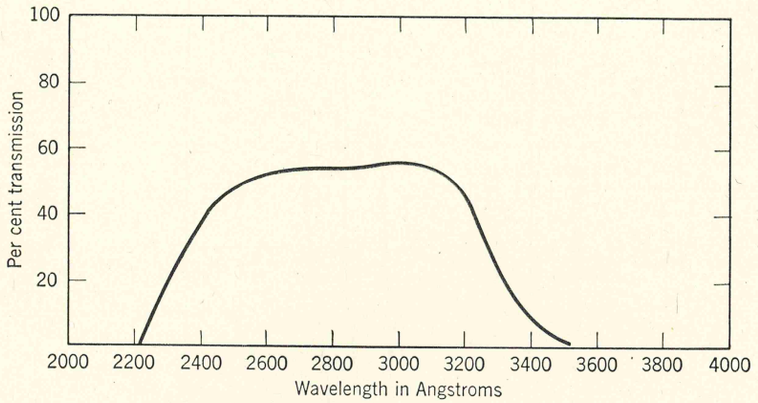

FIG. 14. Transmission of filter consisting of a 5-cm path of aqueous solution containing 240 grams per liter of $NiSo_4 \cdot 6H_4O$ and 45 grams per liter of $CoSO_4 \cdot 7H_2O$. (M. Kasha, *J. Optical Soc. Am.*, **38**, 929, 1948.)

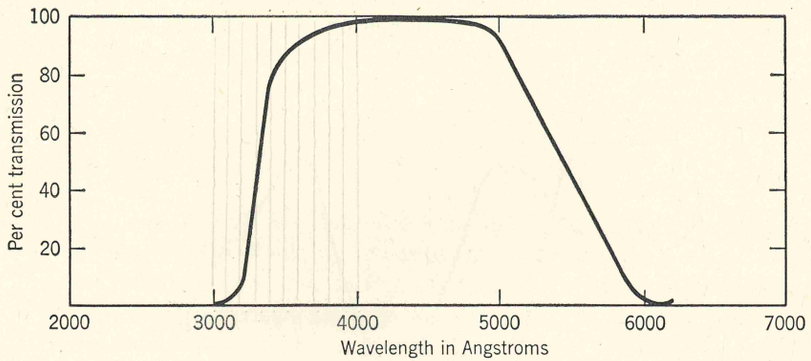

FIG. 15. Transmission of cupric sulfate: 5 cm of solution of $CuSO_4 \cdot 5H_2O$, 100 grams per liter. (M. Kasha, *J. Optical Soc. Am.*, **38**, 929, 1948.)

ing the remaining component. The various components are listed in Table 6.

TABLE 6

ULTRAVIOLET BAND-PASS FILTERS *

Component	Substance	Solution	Optical Path
1	$CuSO_4 \cdot 5H_2O$	100 g/l water	5 cm
2	$NiSO_4 \cdot 6H_2O$	100 g/l water	5 cm
3	$NiSO_4 \cdot 6H_2O$	200 g/l water	5 cm
4	$NiSO_4 \cdot 6H_2O$	300 g/l water	5 cm
5	$NiSO_4 \cdot 6H_2O$ and	240 g/l water	5 cm
	$CoSO_4 \cdot 7H_2O$	45 g/l water	5 cm
Corning Filters			
6	C.S. 7-37 (5860 or 586)		5 mm
7	C.S. 7-51 (5970 or 597)		4 mm
8	C.S. 7-54 (9863 or 986)		3 mm
9	(cn) † (iodide)	200 mg/100 ml water	1 cm
10	Naphthalene	12.8 g/l issoclate	1 cm
11	$K_2Cr_2O_4$	0.200 g/l water	1 cm
12	$KHC_8H_4O_4$	50 g/l water	1 cm
13	CCl_4	Pure liquid	0.5 cm
14	1,4-Diphenylbutadiene	4.24 mg/100 ml ether	1 cm

* M. Kasha, *J. Optical Soc. Am.*, **38**, 929 (1948).

† Cation *x*, 2,7-dimethyl-3,6-diazacyclohepta-1,6-diene iodide, G. Schwarzenback and K. Lutz, *Helv. Chim. Acta*, **23**, 1139 (1940).

The maximum of the transmission band and the combinations of the components are listed in Table 7. (The numbers correspond to those given in Table 6.)

TABLE 7

ULTRAVIOLET BAND-PASS FILTERS *

Wavelength	Filter Components
3600	1 + 6 + 9
3300	2 + 7 + 10
3150	3 + 8 + 11 + 12
2720	4 + 8 + 9 + 13
2560	5 + 14

* M. Kasha, *J. Optical Soc. Am.*, **38**, 929 (1948).

PLASTICS

The transmission curve for acrylic resin, Plexiglass, is shown in Fig. 16. For a 0.1-in. thickness the transmission is about 5 per cent at 2900 A and increases to about 30 per cent at 3100 A. Its overall

transmission decreases approximately 30 per cent on exposure to full sunlight for 2 mo. At the same time the material becomes slightly fluorescent. Figures 17 and 18 show the transmission for several other clear plastics.

Cellulose acetate transmits visible radiation and into the ultraviolet as far as about 3000 A, as shown in Fig. 17. Cellophane is ordinarily

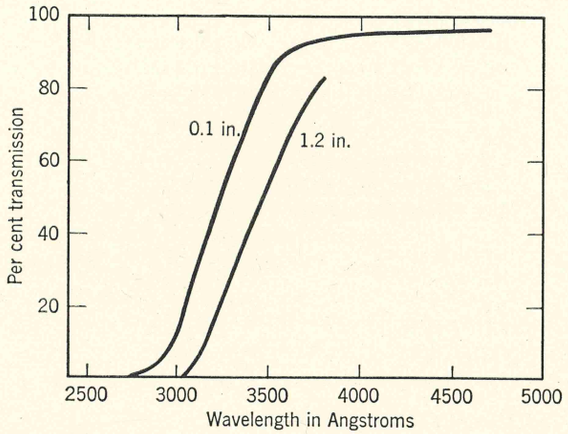

FIG. 16. Transmission of Plexiglass. (Calculated from *Rohm and Haas Catalog.*)

available in two forms, untreated and moisture-proofed. The latter is the form usually used for packaging foods. It is moisture-proofed by treating it with a lacquer which is practically opaque to ultraviolet of shorter wavelengths than 2537 A. The untreated cellophane, on the other hand, transmits about 75 per cent at 2537 A in thickness of 0.001 in. The transmission of 0.005-in. thickness of cellophane at various wavelengths is given in the following table:

Wavelength in Angstroms	2000	2500	3000	3500	4000
Per cent transmission	16	30	47	65	78

It is interesting to note that Chinese window papers show transmission between 20 and 40 per cent at 3000 A.[6]

WATER

Distilled water has a high transmission for ultraviolet down to about 2000 A. Below this the transmission begins to decrease. The absorp-

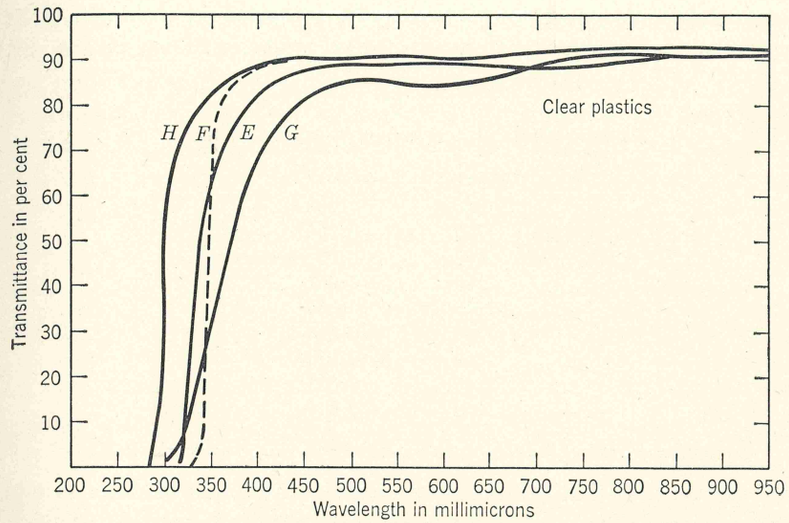

FIG. 17. Spectral transmittance of several clear plastics. *E*. Cellulose nitrate, thickness 0.80 mm. *F*. Cellulose propionate, thickness 0.23 mm. *G*. Ethyl cellulose, thickness 0.79 mm. *H*. Polystyrene, thickness 0.45 mm. (*Natl. Bur. Standards Circ.* 471, 1948.)

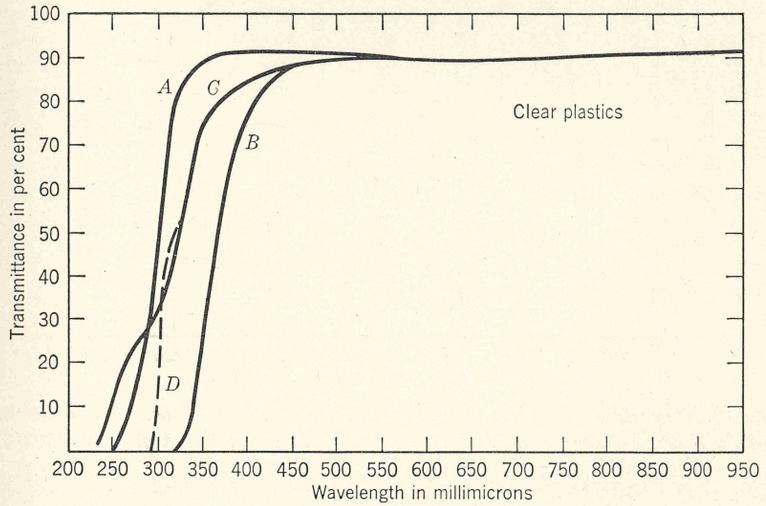

FIG. 18. Spectral transmittance of several clear plastics. *A*. Methyl methacrylate, thickness 1.47 mm. *B*. Allyl alcohol, thickness 3.05 mm. *C*. Cellulose acetate butyrate, thickness 0.41 mm. *D*. Cellulose acetate, thickness 0.50 mm. (*Natl. Bur. Standards Circ.* 471, 1948.)

tion coefficients for various wavelengths are given in Table 8. The transmission curve for 20 mm of distilled water is shown in Fig. 19.

TABLE 8

ABSORPTION COEFFICIENT FOR DISTILLED WATER *

Wavelength	α cm^{-1}
1860	0.688
1930	0.166
2000	0.09
2100	0.061
2200	0.057
2300	0.034
2400	0.032
2600	0.025
3000	0.015

* *International Critical Tables*, McGraw-Hill Book Co., New York, 1926.

The curve shows that for most purposes the absorption of water in thin layers is negligible. At greater depths, however, it becomes appreci-

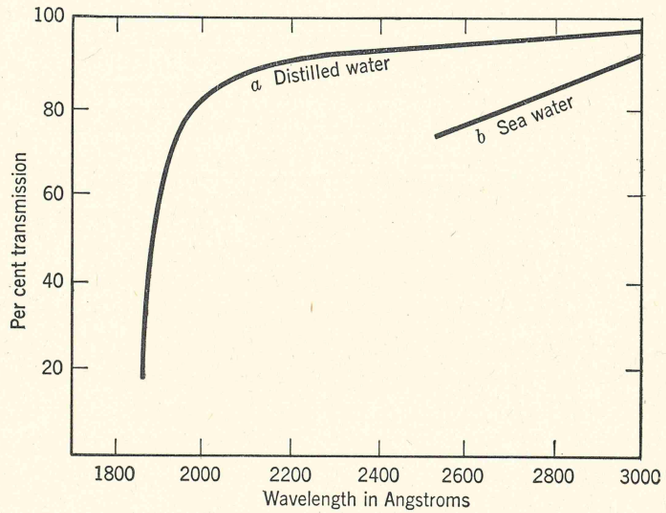

FIG. 19. Transmission of 20 mm of water. *a*. Distilled water. (*International Critical Tables.*) *b*. Sea water. (E. O. Hulburt, *J. Optical Soc. Am.*, **17**, 15, 1928.)

able. For example, the per cent of 2537 A energy which is transmitted to various depths in distilled water is given in the following table:

Depth in inches	3	6	12	24
Per cent transmitted	92	88	78	61

The presence of dissolved salts or of organic matter in water affects the transmission profoundly, so that it is not safe to assume a value for the transmission of any given sample of water. This factor is of great importance in the application of ultraviolet radiation to the sterilization of water. This is illustrated by the data in Table 9, which shows the

TABLE 9 *

THE TRANSMISSION OF GERMICIDAL ENERGY (λ2537) BY WATER FROM VARIOUS CITIES OF THE UNITED STATES

City	Absorption Coefficient α		Per Cent Transmitted by			Depth in Inches for 90 Per Cent Absorption
	Per Cm	Per In.	3 In.	6 In.	12 In.	
Atlanta	0.0258	0.0656	80	66	45	34.8
Cleveland	0.0471	0.120	68	48	23	19.1
Philadelphia	0.0514	0.131	66	45	20	17.5
Buffalo	0.0546	0.139	65	43	19	16.5
Detroit	0.0562	0.143	64	42	18	16.0
Chicago	0.0611	0.155	62	39	15	14.7
Pittsburgh	0.0782	0.199	54	30	9	11.5
LaGrange, Ill.	0.0782	0.199	54	30	9	11.5
New York	0.0804	0.204	53	29	8.5	11.2
Dallas	0.0804	0.204	53	29	8.5	11.2
Portland, Ore.	0.0827	0.210	52	28	7.9	10.9
Denver	0.0896	0.228	49	25	6.4	10.0
Oakland, Calif.	0.102	0.258	45	21	4.4	8.85
Minneapolis	0.142	0.360	33	11	1.3	6.34
Kansas City	0.166	0.422	28	7.8	0.62	5.41
Akron, Ohio	0.177	0.449	26	6.6	0.45	5.09
Los Angeles	0.178	0.452	25	6.5	0.43	5.04
St. Louis	0.184	0.468	24	6.0	0.36	4.88
Boston	0.184	0.468	24	6.0	0.36	4.88

* M. Luckiesh, *Gen. Elec. Rev.*, **47**, 26 (1944).

values of absorption coefficient as well as the per cent of ultraviolet transmitted through various depths of water for a number of municipal water supplies at 2537 A. As shown in the second column of the table, the variation in absorption coefficient for different samples of water is about sevenfold.[7] As a result of this variation 1 ft of water may transmit anywhere from 0.36 per cent to 45 per cent of the incident ultraviolet.

The treatment which water receives greatly affects the transmission, and for this reason great precautions must be taken in collecting samples. Contamination from stoppers, filter paper, and the like may reduce the transmission by a large factor. Luckiesh found that contamination from an ordinary cork reduced the transmission of 5 inches of Cleveland's city water stored in a glass bottle from 53 to 34 per cent at 2537 A. Filtering distilled water through two filter papers reduced the transmission from 95 to 58 per cent.

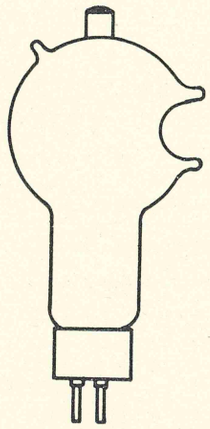

FIG. 20. Thin glass window in phototube bulb.

Figure 19 also shows the transmission for 20 mm of sea water. The transmission is considerably less than that of distilled water on account of the presence of dissolved salts. The penetration of light into natural water is of considerable biological interest. It determines the photosynthesis of aquatic plants, the formation of vitamin D stored in fish liver oils, and the movements of photosensitive animals. Measurements in various parts of the Atlantic Ocean showed that the Sargasso Sea was the most transparent part of the ocean where measurements had been made. The values of α in the equation $I/I_0 = e^{-at}$ where t = thickness in meters were:

Red	6000–7000 A	0.082[8]
Green	4900–6200 A	0.049
Violet	3100–4500 A	0.048

THIN WINDOWS

Advantage is taken of the exponential character of the transmission curve to obtain high ultraviolet transmission in lamp or phototube bulbs without using special ultraviolet-transmitting glass. This is done by making very thin glass windows. These windows sometimes take the reentrant form shown in Fig. 20 in order to obtain greater strength. They may have a thickness in the thinnest portion of only a few thousandths of an inch. In spite of the fact that the glass of which they are made has a low transmission for ultraviolet in ordinary thicknesses, the transmission for the extremely thin layer may be quite high. For example, if we assume an absorption coefficient for a glass at 2537 A of 40, 1 mm would be nearly opaque to this radiation, transmitting only 2 per cent. However, in a layer 5×10^{-3} cm its transmission would be 81 per cent. In spite of the thinness of these windows, they will

withstand reasonable handling. Their chief disadvantage other than their fragility is their relatively small size. Modern methods of handling glass should make larger windows possible.

PROTECTIVE GLASSES

It is often desirable to have materials which are strong absorbers of ultraviolet, especially for the protection of the eyes. This is particu-

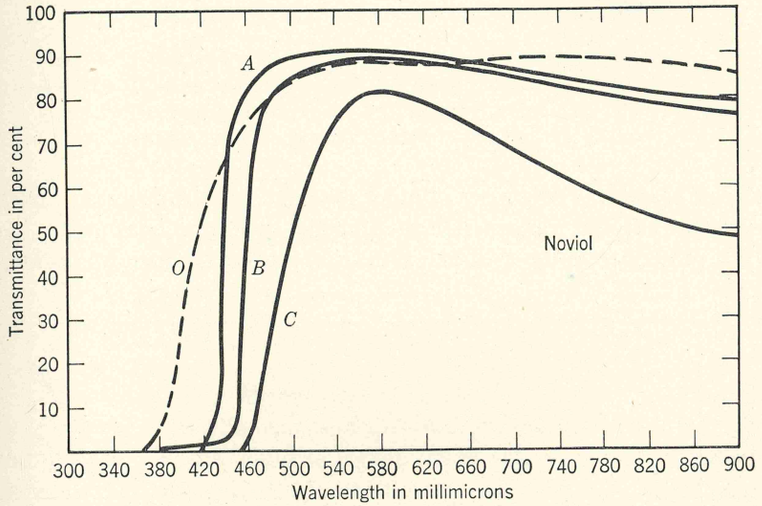

FIG. 21. Spectral transmittance of Noviol glass. Noviol *O*, thickness 2.63 mm. Noviol *A*, thickness 1.90 mm. Noviol *B*, thickness 2.89 mm. Noviol *C*, thickness 3.05 mm. (*Natl. Bur. Standards Circ.* 471, 1948.)

larly true in industrial applications such as welding, as well as for protection from ordinary sunlight. A large number of protective glasses have been developed for these purposes. Many of them are designed to absorb strongly in various portions of the visible and infrared regions. The earliest of these glasses was developed by Crookes in 1914.[9] The transmission of some Crookes glasses is given in Table 3. Since then literally hundreds of others have been developed. Their characteristics are described in "Spectral-Transmissive Properties and Use of Eye-Protective Glasses" by R. Stair in *Natl. Bur. Standards Circ.* 471, 1948. The transmission of Noviol, slightly yellow glasses which cut off sharply at the edge of the ultraviolet, is shown in Fig. 21 and Table 10. Figure 22 shows the transmission of several samples of

TABLE 10

TRANSMISSION OF NOVIOL GLASSES

Wavelength in Angstroms	CG 338 Yellow Noviol *C*	CG 038 Lt Yellow Noviol *A*	CG 306 Noviol *O* 2 mm
3400			
3600			0
3800			0.120
4000			0.473
4200		0	0.635
4400	0	0.55	0.745
4600	0.38	0.702	0.795
5000	0.765	0.787	0.835
6000		0.825	0.880

Polaroid glasses. For glasses of other tints and various degrees of ultraviolet and infrared transmission the bulletin should be consulted.

For protection of the eyes and skin from limited exposure to ordinary

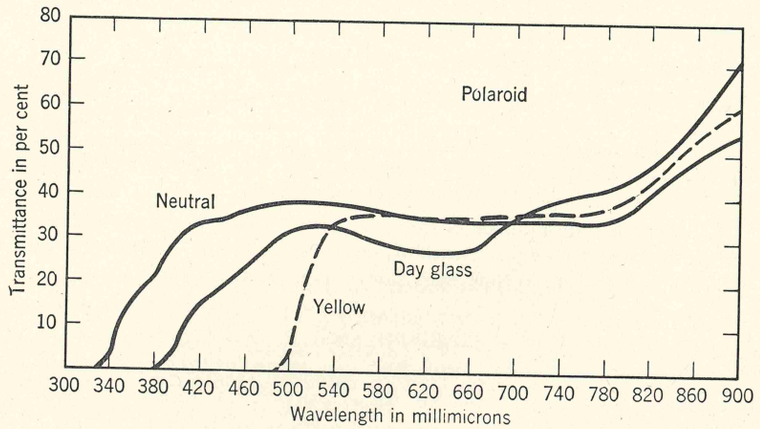

FIG. 22. Spectral transmittance of Polaroid glasses. Neutral Polaroid, thickness 5.20 mm. Polaroid Day glass, thickness 2.28 mm. Yellow Polaroid, thickness 5.65 mm. (*Natl. Bur. Standards Circ.* 471, 1948.)

ultraviolet lamps common window glass is usually adequate. However, this transmits considerable intensities of near ultraviolet and is not sufficient protection for welding operations or against glare.

FOOD AND BEVERAGES

The transmission of various foods and beverages is important in considering the practicability of disinfecting or sterilizing them by means of ultraviolet radiation. Table 11 calculated from data given

TABLE 11

Substance	α cm^{-1}	Inches for 90% Absorption
Wine, red port	28	0.03
Wine, sherry	9	0.1
Wine, muscatel	7	0.13
Wine, blackberry	28	0.03
Beer, 3 brands	16	0.055
Beer, 3 brands	15	0.06
Coca-Cola, bottled	31	0.03
Apple juice	17	0.05
Sugar syrup, brown	38	0.02
Sugar syrup, colorless	2.5	0.38
Milk, raw whole	290	0.003
Vinegar, brown	6.5	0.14
Vinegar, brown	5.1	0.18
Vinegar, colorless	1.5	0.60
Egg white	4.3	0.2

by Luckiesh [10] gives the values of the absorption coefficient α at 2537 A and the depth of the liquid in inches which will absorb 90 per cent of the energy at this wavelength for various foods and beverages.

AIR

The absorption of ultraviolet in air is insignificant over distances used in the laboratory at wavelengths greater than 2000 A. Over greater distances, however, the absorption may be appreciable, and, as discussed in Chapter 4, it has a profound effect on the nature of the solar spectrum. It is made up of two parts, a permanent part due to the atmospheric gases and a variable part due to the particles which cause haze. At wavelengths below 2000 A the absorption becomes very large, chiefly owing to the oxygen.

Measurements of the transmission over a 400-meter path on the edge of the Potomac River near Washington, D. C., were made by Dawson, Granath, and Hulburt.[11] Their values for the per cent transmission over this path under conditions of good and poor visibility are shown in Fig. 23. Good visibility is defined as conditions under which a dark-colored object could be distinguished at distances greater than 15 km; poor visi-

bility is defined as conditions under which a dark-colored object could be distinguished at about 8 km. From the figure, it can be seen that the absorption increases with decreasing wavelength and is much more marked when the air is hazy than when it is clear.

The permanent part of the absorption due to molecular scattering by the atmospheric gases may be calculated by a formula derived by Lord

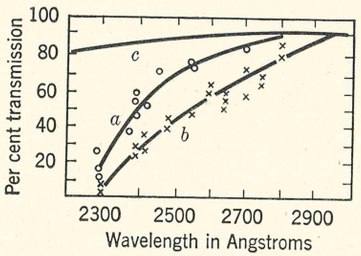

FIG. 23. Transmission through 400 meters of air. *a*. Good visibility. *b*. Poor visibility. *c*. Calculated. (L. H. Dawson, L. P. Granath, and E. O. Hulburt, *Phys. Rev.*, **34**, 136, 1929.)

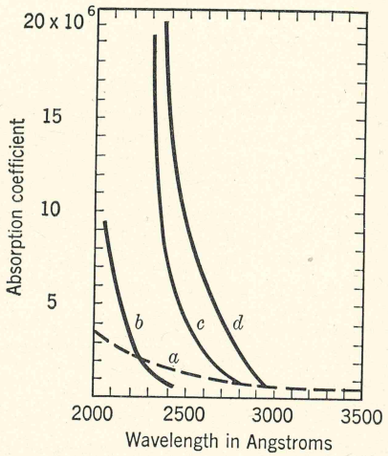

FIG. 24. Absorption coefficient for air as a function of wavelength. *a*. Calculated. *c*. Observed, clear atmosphere. *b*. Extension of *c* to 2050 A; ordinates should be multiplied by 10. *d*. Observed, hazy atmosphere. (L. H. Dawson, L. P. Granath, and E. O. Hulburt, *Phys. Rev.*, **34**, 136, 1929.)

Rayleigh.[12] The curve for the transmission of air based on this formula is also shown in Fig. 23. In clear air at above 3000 A the observed transmission agrees with the value calculated for molecular scattering according to Rayleigh's formula. At shorter wavelengths the observed absorption is considerably greater than the calculated value. Values of absorption coefficient as a function of wavelength are shown in Fig. 24. The transmission for any distance may be calculated from these by the usual formula $I/I_0 = e^{-\alpha w}$.

Calculations show that the absorption of ultraviolet in the lower atmosphere is not sufficient to account for the complete absence of wave-

lengths shorter than 2800 A in the solar spectrum. This is the result of absorption by the ozone in the upper atmosphere. The ozone absorption band extends from 2900 to 2200 A. Ozone is quite transparent for wavelengths shorter than 2200 A. The absence of radiation shorter than 2200 A at the earth's surface is readily accounted for by absorption in the lower atmosphere.

Christiansen Filter

This type of filter makes use of a principle quite different from simple absorption for segregating a narrow region of the spectrum. The principle was discovered by Christiansen in 1884 but little use was made of it till recently. The Christiansen filter consists of a suspension of small crystals in a suitable transparent medium. Owing to differences in index of refraction between the solid and the liquid, radiation is scattered, and relatively little passes directly through the suspension. If, however, the dispersion curves of the solid and the liquid cross, then at the point of intersection where both the solid and the liquid have the same index of refraction the filter acts as an optically homogeneous medium. Radiation of this wavelength is transmitted without deviation, whereas longer and shorter wavelengths are refracted and scattered.

Since the indices of refraction of the solid and the liquid respond differently to changes in temperature, the intersection of the two dispersion curves and consequently the wavelength transmitted by the filter will vary with temperature. The variation may amount to 100 A per degree.

The desired radiation is surrounded by symmetrical halos of the undesired radiation. The effectiveness of the filter depends in part on the angle at which light strikes the filter and on the solid angle included in the observation method. The filter is most efficient if the light emerging perpendicular to the filter is used. The advantage of Christiansen filters is that their transmission lies in a relatively narrow region.

A solution of 56 per cent benzene and 44 per cent ethanol containing amorphous silica at 20°C transmits at 3600 A.

Interference Filters

Still another type of filter which is useful for transmitting in a narrow band is the interference filter. This consists essentially of a pair of thin semi-transparent metal films separated by a distance of the order of a few wavelengths. In practice these films are formed by evaporation and are mounted between glass plates for support. By proper choice of spacing, it is possible to produce filters which transmit in a narrow band in any desired part of the spectrum between 3700 and 7000 A. The

maximum transmission is about 35 per cent. The half width of the band is 100–150 A, i.e., at a wavelength 50 to 75 A on either side of the maximum the transmission is 50 per cent of the peak value.[13]

Skin Protective Coatings

Numerous sun-tan preparations are used for the purpose of protecting the skin from short-wave erythemal radiation and permitting the passage of the longer wavelength tanning radiation. Obviously, these preparations cannot accelerate the tanning process, but they do make possible prolonged exposure without erythema. During the war there was a particular necessity for a means of prophylaxis of sunburn for men marooned on life rafts or in the desert after airplane crashes. The requirements for such coatings were that they must be nontoxic, must offer the maximum protection and coverage per unit volume and per unit weight, must be capable of simple packing and not being harmed by freezing, must be highly absorbing in the 2900–3200 A region and not easily washed off. These requirements were met by dark red vet. petrolatum which is nonirritating and adheres to the skin. This is quite opaque to erythemal energy.[14] It served as complete protection to the equivalent of 20 hr of maximum Cleveland sunshine.

Phenyl salicylate (salol) was found to be excellent protection when put up in a 10 per cent cream.

The transmission of several different coatings is given in Table 12.

For peacetime purposes, some of the above requirements are not applicable and factors such as ease of application and removal, odor, and appearance are more important.

Transmission of Skin

Measurements of the transmission of the human skin are attended with great difficulty, and results by various observers differ in details although they agree in the main. One of the difficulties involved in the measurements is that the skin is not a transparent medium and a considerable portion of the radiation is scattered. The transmission is greatly influenced by the condition of the skin. The transmission of the different layers is shown in the curves of Fig. 25 and in Table 13.

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3. E. A. Taft, private communication.
4. F. Zernike, *Physica*, **8**, 81 (1928).

TABLE 12

Transmission of Skin Protective Coatings *

Specimen and Thickness	2967 A	3022 A	3130 A	3342 A	3650 A
Petroleum jellies					
Colorless, 0.03 mm	65	69	71	88	91
Very light amber, 0.03 mm	32	32	55	88	94
Medium amber, 0.03 mm	25	30	44	74	89
Dark amber, 0.03 mm	5	9	21	52	75
Orange-red, 0.03 mm	0	0	2	16	58
Mixtures of materials					
Mixture D, 0.03 mm	0	0	0	1	3
Mixture J, 0.03 mm	0	0	0	3	29
Mixture J, 0.06 mm	0	0	0	0.3	7
Mixture L, 0.03 mm	0	0	0.1	6	44
Mixture L, 0.06 mm	0	0	0	0	0.3

Mixture D: zinc oxide 33%; phenyl salicylate 10%; and petrolatum flava 57%.
Mixture J: phenyl salicylate 67%; petrolatum 33%.
Mixture L: phenyl salicylate 33%; zinc oxide 50%; and petrolatum flava 17%.

* M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, page 92.

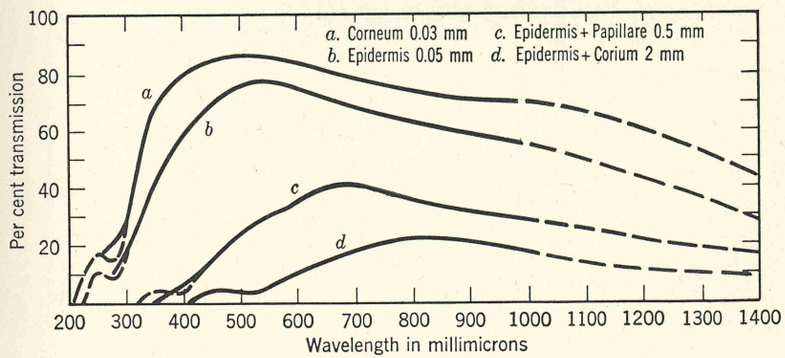

Fig. 25. Transmission of various layers of the skin. (A. Bachem and C. I. Reed, *Am. J. Physiol.*, **97**, 86, 1931.)

TABLE 13 *

PERCENTAGES OF INCIDENT ENERGY TRANSMITTED THROUGH THE LAYERS OF THE SKIN

Layer	Wavelength A / mm	2000	2500	2800	3000	4000	5500	7500	10,000	14,000
Corneum	0.03	0	19	15	34	80	87	78	71	44
+ Malpighi	0.05	0	11	9	16	57	77	65	65	28
+ Corium	2.0	0	0	0	0	1	5	21	17	8
+ Subcutaneous	2.5	0	0	0	0	0	0	1	0	0
		All absorbed by corneum. No radiation reaching germinatium.	Greatest absorption in stratum corneum. Some radiation reaches corium (papillae). No radiation reaches subcutaneous layers.		Relatively large absorption in stratum Malpighi.		Minimum absorption in stratum corneum, most radiation absorbed in corium. Pronounced radiation reaching subcutaneous layers.		Strongly increasing absorption in upper layers, decreasing in lower layers. Pronounced radiation reaching subcutaneous layers.	

* Bachem and Reed, *Am. J. Physiol.*, **97**, 86 (1931).

5. A. M. Bass, *J. Optical Soc. Am.*, **38**, 977 (1948).
6. Ch'en Shang-yi, *J. Optical Soc. Am.*, **25**, 67 (1935).
7. M. Luckiesh, *Gen. Elec. Rev.*, **47**, 26 (1944).
8. R. H. Oster and G. L. Clark, *J. Optical Soc. Am.*, **25**, 84 (1935).
9. W. Crookes, *Trans. Roy. Soc. (London)*, **214**, 1 (1914).
10. M. Luckiesh, *Applications of Germicidal Erythemal and Infrared Energy*, Van Nostrand, 1946.
11. L. H. Dawson, L. P. Granath, and E. O. Hulburt, *Phys. Rev.*, **34**, 136 (1929).
12. Lord Rayleigh, *Phil. Mag.*, **47**, 375 (1899).
13. L. N. Hadley and D. M. Dennison, *J. Optical. Soc. Am.*, **38**, 483 (1948).
14. M. Luckiesh and A. H. Taylor, *J. Am. Med. Assoc.*, **130**, 1 (1946).

6 Reflection

Metals

Many substances which are good reflectors for visible radiation are very poor reflectors of ultraviolet. The ordinary glass mirror, silvered on the back surface, is quite unsuitable for ultraviolet because of the absorption of the radiation in the glass. For this reason, mirrors for the reflection of ultraviolet are necessarily "front surface" mirrors or polished metals.

Most metals are good reflectors of ultraviolet over a very large portion of the spectrum, provided that their surfaces are clean and free from oxide or tarnish. In general, the reflection coefficient of metals increases with increasing wavelength from a few per cent in the far ultraviolet to 80–90 per cent in the visible. There are very few large irregularities in metallic reflection curves. Silver is one of the notable exceptions to this rule having a very pronounced minimum in its reflection curve at 3150 A.

Many considerations other than reflection alone enter into the choice of materials for metallic reflectors. These include the ease of working the metal into the desired shape, ease of polishing, resistance to corrosion and abrasion, strength, weight, and cost.

In some cases reflectors are formed by evaporating metals onto suitably prepared surfaces. Thus it is possible to form a surface having the desirable optical properties of one metal on a foundation having the desirable mechanical properties of another substance. For example, telescope mirrors are made by evaporating silver or aluminum onto a glass surface. In some types of projection lamps, silver or aluminum or copper is evaporated on the wall of the bulb to provide a reflecting surface. Although evaporated surfaces usually have higher reflection coefficients than the bulk materials, their use is not justified for most commercial applications.

The reflection of a few metals at the wavelength 2967 A is given in Table 1.

TABLE 1

Metal	Per Cent Reflection * at 2967 A
Chromium-plated metal	43–55
Nickel-plated metal	29–34
Silver-plated metal	13
Stainless steel	30
Rhodium	45
Allegheny metal	30–36

* A. H. Taylor, *J. Optical Soc. Am.*, **24**, 193 (1934).

Figure 1 shows the reflection of silver, chromium, nickel, and stainless steel as a function of wavelength. Chromium, nickel, and stainless steel are resistant to corrosion and abrasion. Silver is soft and tarnishes

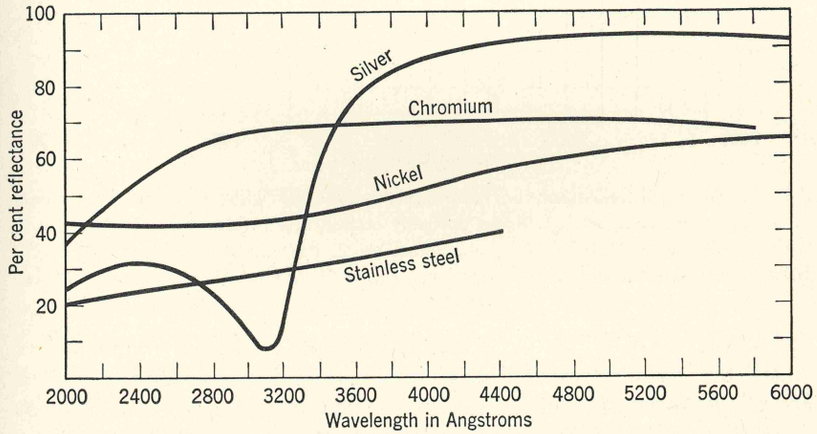

Fig. 1. Reflection from silver, chromium, nickel, and stainless steel. (M. Luckiesh, *J. Optical Soc. Am.*, **19**, 1, 1929.)

readily. The minimum in its curve around 3200 A makes it unsuitable for some purposes, but its reflection is very high in the near ultraviolet. That silver can easily be deposited by chemical methods is a great advantage in many applications.

Aluminum

Aluminum is one of the most satisfactory reflectors for most purposes. It is easily shaped, light in weight, has a high reflectance, and is very

resistant to corrosion. The reflection of aluminum depends to some extent upon the way in which the surface has been treated. The reflectance of ordinary rolled aluminum sheet can be increased by two or three per cent by an electrolytic etching process known as brightening, which removes impurities from the surface. The surface can be protected from weathering by the anodic formation of a thin coat of oxide. This increased corrosion resistance is obtained at the cost of a decrease in the reflection. The reduction is more marked in the ultraviolet than in

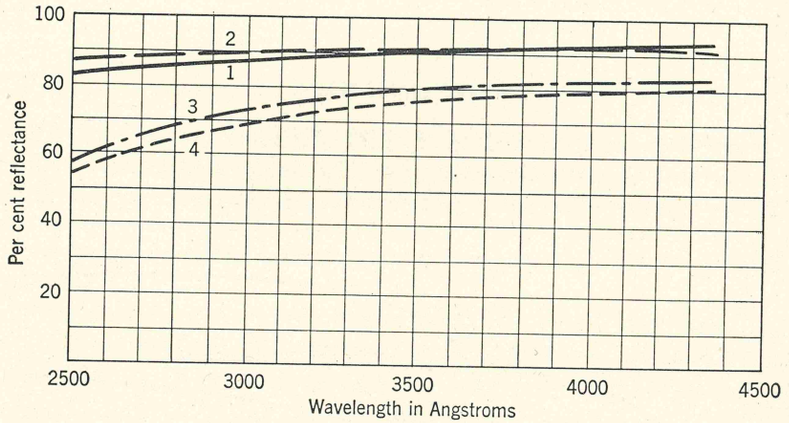

FIG. 2. Spectral reflectance of aluminum with and without Alzak treatment. 1. Bright rolled 2s sheet. 2. Same diffusely etched and brightened. 3. Same as 2 with anodic coating 0.00016″. 4. Same as 2 with anodic coating 0.00022″. (M. Luckiesh, *Germicidal, Erythemal and Infrared Energy,* D. Van Nostrand Co., New York, 1946.)

the visible. This electrolytic brightening and oxidation treatment [1] is called the Alzac * process. Figure 2 shows the reflection of rolled sheet, electrolytically brightened, and anodic-coated aluminum, respectively. The anodic-coated material has a reflectivity of 65 to 75 per cent at 2537 A. With hard alloys of aluminum, a reflectivity of 89 per cent can be obtained.

Aluminum paints are also reasonably good reflectors of ultraviolet. Nine brands studied by Luckiesh had reflection coefficients at 2552 A ranging from 48 to 66 per cent. Intense exposure to 2537 A radiation increased the reflection coefficient at 2537 A appreciably, 12 per cent on the average. The reflection at longer wavelengths was only slightly affected. This effect is probably due to changes produced in the vehicle in which the aluminum flakes are suspended.

* Alzac is a trademark registered by the Aluminum Co. of America.

Evaporated Metal Films

The ease with which metals can be evaporated is an important factor in determining their usefulness as reflectors. The evaporation process consists in heating the metal in vacuo to a sufficiently high temperature to cause rapid vaporization. This is done by placing it in what is the equivalent of a small furnace or inside a coil of very refractory metal such as tungsten. The object to be coated is placed a few inches away from the vaporizer. The metallic vapor condenses on it, forming a

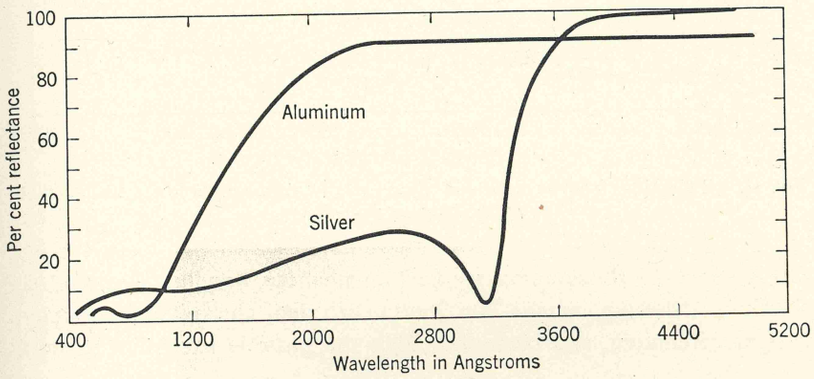

FIG. 3. Reflection from evaporated films of silver and aluminum. (J. B. Sabine, *Phys. Rev.*, **55**, 1064, 1939.)

highly polished reflecting surface. Since this process must be carried out in a high vacuum, it is not suitable for large reflectors.

Aluminum is among the most readily evaporated metals. It can be evaporated from a tungsten filament and deposits on suitable surfaces in the form of a highly reflecting mirror. The reflection is about 90 per cent from the visible down to about 2537 A where it begins to decrease, falling to about 30 per cent at 1200 A as shown in Fig. 3.[2] The evaporated surfaces are rather soft but can be hardened and made resistant to scratching by rubbing gently with absorbent cotton moistened with water. Between 1200 and 3600 A its reflection is greater than that of any other metal. Above 3600 A it is exceeded only by that of silver.

Silver also is very easily evaporated but as already noted is easily scratched and tarnished. Its reflection is also shown in Fig. 3. The reflectivity of chemically deposited silver on bulk metal is practically the same as for evaporated films.

Curves for evaporated deposits of platinum, palladium, and nickel are

shown in Fig. 4. All three of these metals are fair ultraviolet reflectors, platinum and palladium being two of the best in the far ultraviolet. All three are durable and corrosion resistant.

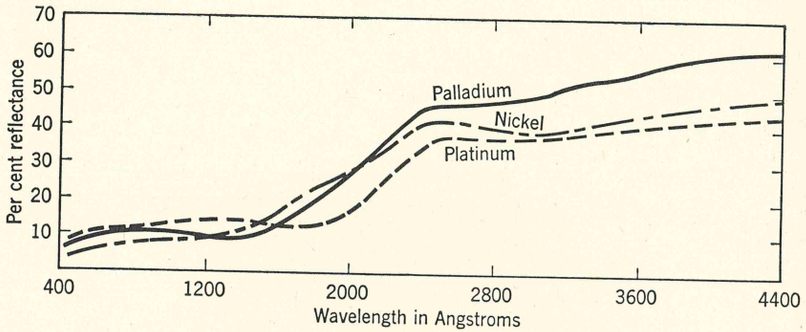

FIG. 4. Reflection from evaporated films of platinum, palladium, and nickel. (J. B. Sabine, loc. cit.)

Figures 5–11 show curves for lead, manganese, beryllium, iron, gold, titanium, tellurium, magnesium, cadmium, zinc, chromium, antimony, copper, zirconium, and bismuth. With the possible exception of iron,

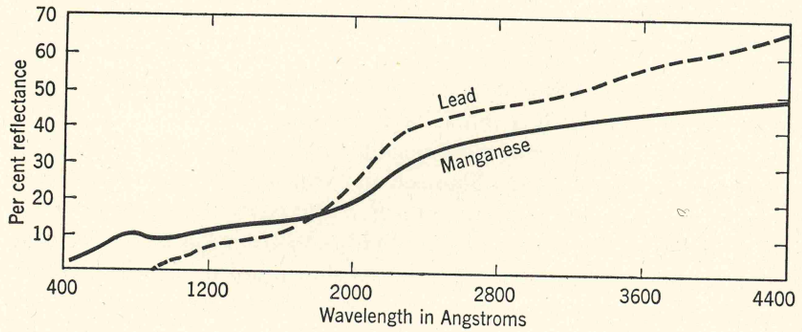

FIG. 5. Reflection from evaporated films of lead and manganese. (J. B. Sabine, loc. cit.)

beryllium, and chromium, none of these are used as mirrors to any great extent. Titanium and zirconium are rather difficult to evaporate. Cadmium, lead, zinc, bismuth, and magnesium are very soft and subject to deterioration when they are exposed to air.

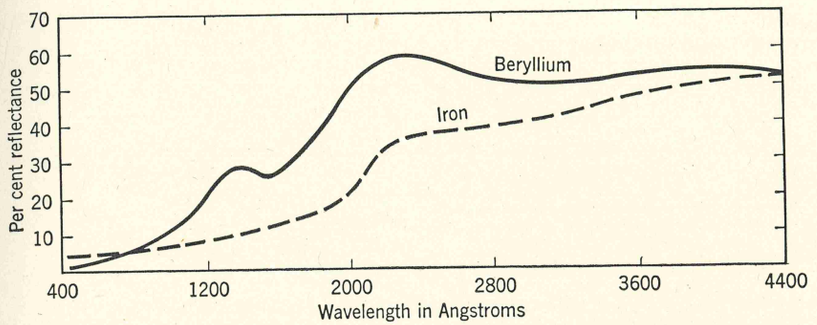

FIG. 6. Reflection from evaporated films of beryllium and iron. (J. B. Sabine, loc. cit.)

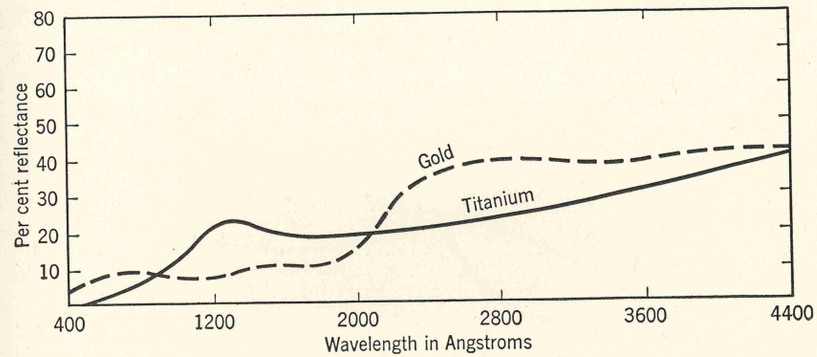

FIG. 7. Reflection from evaporated films of gold and titanium. (J. B. Sabine, loc. cit.)

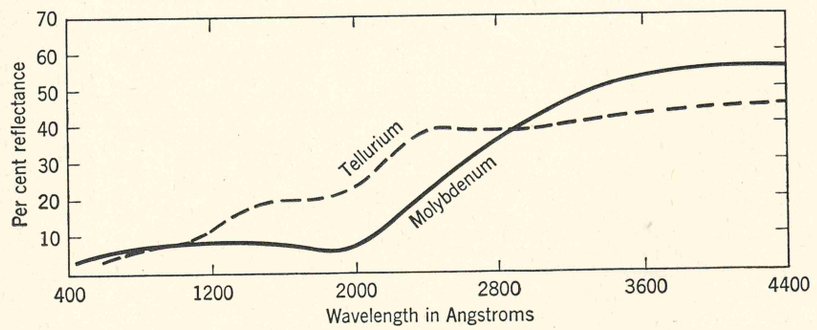

FIG. 8. Reflection from evaporated films of molybdenum and tellurium. (J. B. Sabine, loc. cit.)

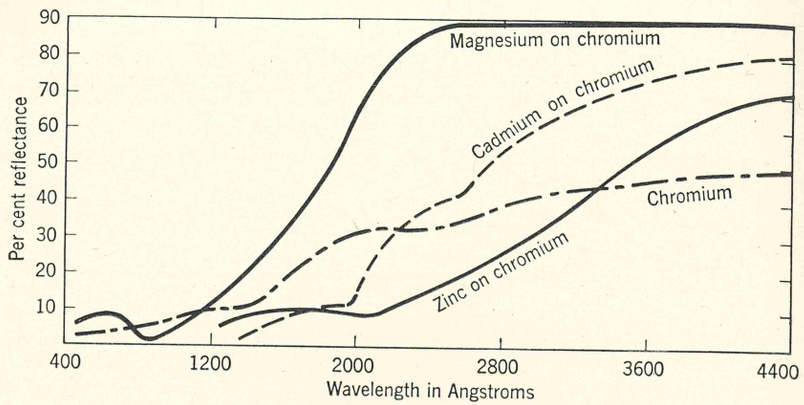

FIG. 9. Reflection from evaporated films of cadmium, magnesium, zinc, and chromium. (J. B. Sabine, loc. cit.)

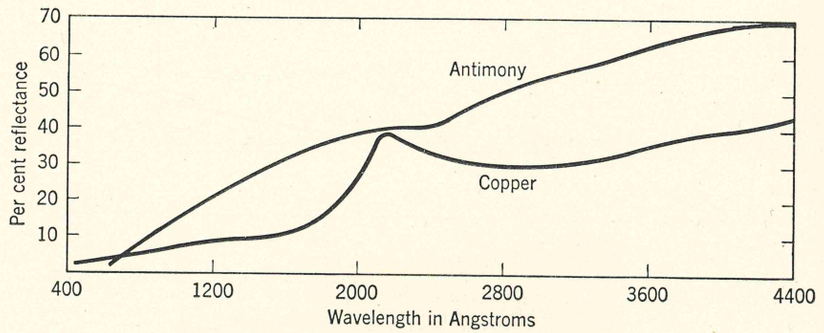

FIG. 10. Reflection from evaporated films of antimony and copper. (J. B. Sabine, loc. cit.)

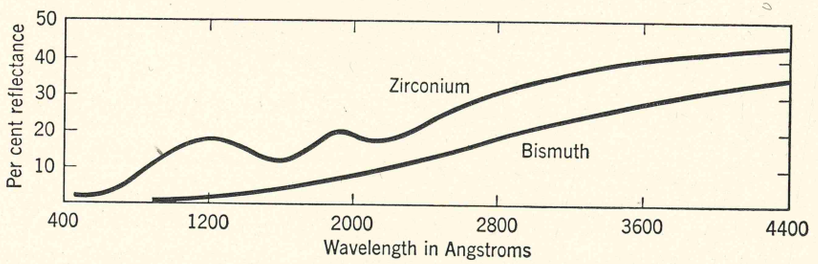

FIG. 11. Reflection from evaporated films of bismuth and zirconium. (J. B. Sabine, loc. cit.)

GLASS

Figure 12 shows the reflection from glass at normal incidence. The reflection from the surface of glass or any other transparent medium

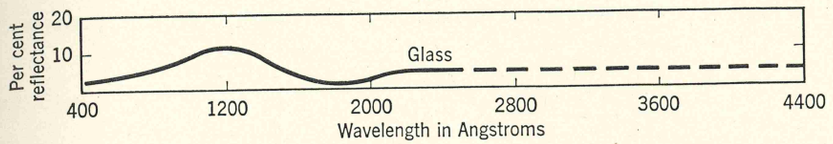

FIG. 12. Reflection from glass at normal incidence. (J. B. Sabine, loc. cit.)

varies greatly with angle of incidence. The reflectance from glass at various angles of incidence is shown in *a* in Fig. 13. As can be seen from the figure, it becomes very high at or near grazing incidence. The curve for water is similar to that for glass as shown in *b* in Fig. 13.

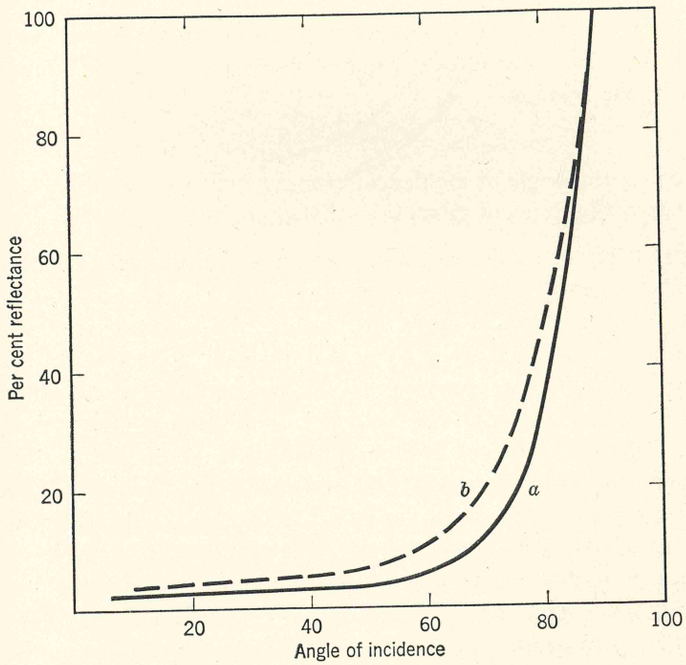

FIG. 13. *a*. Reflection of ultraviolet (3082 A) from the surface of glass at various angles of incidence. *b*. Reflection of ultraviolet from the surface of water at various angles of incidence.

Total Internal Reflection

Radiation can easily be "piped" through quartz rods by making use of total internal reflection. When radiation passes from a dense to a less dense medium, it is refracted away from the normal as shown in *a* in Fig. 14. If the angle of incidence is increased, a critical angle is

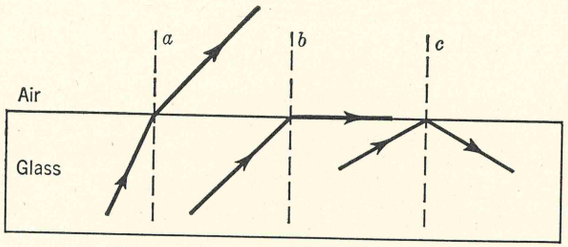

Fig. 14. Total internal reflection.

reached at which the emerging radiation just grazes the surface as shown in *b* in Fig. 14. The critical angle of incidence i_c for this condition is given by the relation

$$\sin i = 1/u$$

where i = the angle of incidence.
u = the index of refraction of the medium.

For any angle of incidence greater than this critical angle the radiation is totally reflected internally as shown in *c* in Fig. 14. In the case of quartz in air, the critical angle for total internal reflection is about 38°. Accordingly, radiation may be passed through a quartz rod without escaping from the rod, provided that the bends in the rod are sufficiently gradual so that the angle of incidence is never less than the critical angle. The path of light around a bend in a quartz rod is shown in Fig. 15. The losses in intensity depend chiefly on the absorption in the transmitting medium. Thus the loss is chiefly due to the absorption in the long quartz path. Accordingly, visible and near ultraviolet radiation are transmitted fairly well, but the method is not suitable for short ultraviolet. About 88 per cent of visible radiation is transmitted through a 1-ft quartz rod, whereas only ½ per cent is transmitted at 2800 A.

This principle is made use of in applicators for illuminating inaccessible places, such as body cavities.

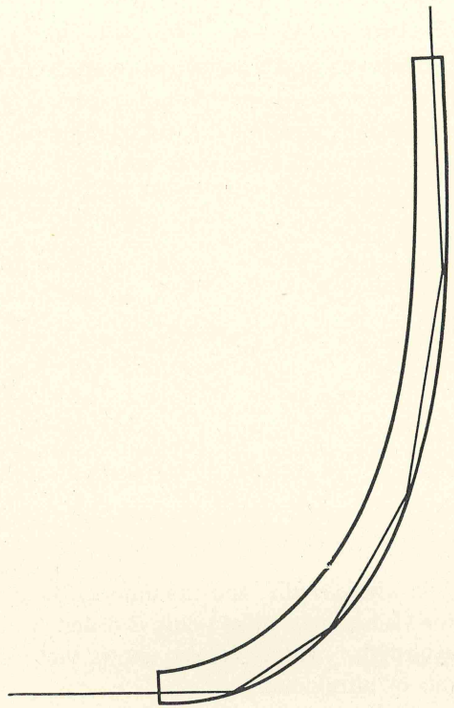

Fig. 15. Total internal reflection around a bend in a quartz tube.

Protection of Metal Mirrors

The surface of metal mirrors may be protected by a thin layer of silicon dioxide. This is formed by evaporating silicon monoxide which subsequently oxidizes to dioxide.[3] If this layer is formed by slow evaporation, it has a high transmission for ultraviolet, but if formed too rapidly it is quite opaque.

Pigments

The reflection of ultraviolet from pigments covers a range from almost zero up to more than 90 per cent. This is often a matter of considerable importance in installations of germicidal lamps where the reflection from walls and ceilings may be highly undesirable. The reflectance to visible radiation is no guide to the performance of these materials in the ultraviolet. Table 2 gives the reflection from a number of white pigments and other materials at several wavelengths in the ultraviolet. The table shows that ordinary white wall plaster has a reflection of 46

TABLE 2

REFLECTION OF WHITE PIGMENTS AND OTHER MATERIALS *

	2537 A in Per Cent	2967 A in Per Cent	3650 A in Per Cent	Light in Per Cent
Pressed zinc oxide	2.5	2.5	4	88
Barytes	65	70	77	86
Titanium oxide	6	6	31	94
Pressed magnesium oxide	77	86	87	93–95
Smoked magnesium oxide	93	93	94	95–97
Pressed calcium carbonate	78	83	86	96
White wall plaster	46	65	76	90
S.W. white Decotint paint	33	41	58	79
Kalsomine white water paint	12	20	40	70
Albastine white water paint	10	14	45	78
White porcelain enamel	4.7	5.4	63	80
Flat black Egyptian lacquer	5	5	5	5
Five samples of wallpaper	18–31	21–40	33–50	55–75

* M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York, 1946, p. 383.

per cent at 2537 A, whereas zinc and titanium oxide which are equally good reflectors for visible light reflect only 2.5 and 6 per cent, respectively, at this wavelength. The table also shows that wallpapers reflect significant amounts of ultraviolet.

In general, oil-vehicle paints tend to have low reflectances, regardless of the pigments, because of the absorption of the oil. On the other hand, some paints using synthetic plastic vehicles with high ultraviolet transmission may have high reflectances. Walls surfaced with gypsum products tend to have high reflectances.

Table 3 shows the ultraviolet reflectance of a number of dry white pigments in the region between 2800 and 3200 A. These measurements were made with the unresolved radiation from an S-1 lamp as a source and a cadmium phototube as a detector. Because of the relative strength of the mercury lines in this region and the response characteristic of the phototube, these measurements may be assumed to be predominantly at the wavelength 3024 A.

The difference between the two white pigments, zinc oxide and white lead, is quite striking. Although both of the pigments are very good reflectors for visible radiation, the zinc oxide reflects only 3 per cent of the ultraviolet, whereas the white lead reflects about 60 per cent. No assumptions regarding the reflection of white pigments should be made without investigating their composition. Colored pigments are almost

TABLE 3

ULTRAVIOLET REFLECTANCE OF DRY WHITE PIGMENTS *

Pigment	Ultraviolet Reflectance Factor in Per Cent
Lead-free zinc oxide	3
35% leaded zinc oxide	4
Zinc sulfide	6
* Titanox B	6
* Lead titanate	6
Titanium dioxide	7
* Titanox C	7
Lithopone	8
Antimony oxide	17
* Zirconium oxide (commercial)	41
Diatomaceous silica (Celite 110)	45
* Basic sulfate white lead	48
China clay	54
* Aluminum oxide	55
* Basic carbonate white lead (Dutch process)	62
* Aluminum hydroxide	67
* Zirconium oxide, C.P.	78
* Magnesium carbonate (commercial)	81

* D. F. Wilcock and W. Soller, *Ind. Eng. Chem.*, **32,** 1446 (1940).

invariably poor reflectors of ultraviolet. Of a series of 38 studied by Stutz,[4] the only one which had a reflectance of as much as 25 per cent at 3131 A was turquoise blue. At 2536 A, turquoise blue had a reflectance of 22 per cent, whereas none of the others exceeded 7½ per cent.

Two reflectors which are common in the laboratory in spectroscopy because of their high reflectance in the visible and the ultraviolet are magnesium oxide and magnesium carbonate. Curves for the reflection of these are shown in Fig. 16.[5] The magnesium oxide has a reflectance of over 90 per cent between 2600 and 4000 A.

The reflecting power of a paint depends upon other factors than the pigment alone. The fundamental requirements which must be met by an ultraviolet-reflecting paint are:

1. Particles of the pigment must be low in absorption (except metallic pigments), so that by multiple reflection and refractions a large portion of the incident radiation is returned.

2. The binder or vehicle must be transparent to the radiation to be reflected.

3. The difference in refractive index between pigment and medium must be large so that reflection and refraction at pigment-medium interfaces will be appreciable.

The properties of a paint depend not only on the nature of the pigment but also upon its state of aggregation and on the amount of it contained in the paint. The ultraviolet reflection increases rapidly with the amount of pigment contained. However, a limit to the amount is set

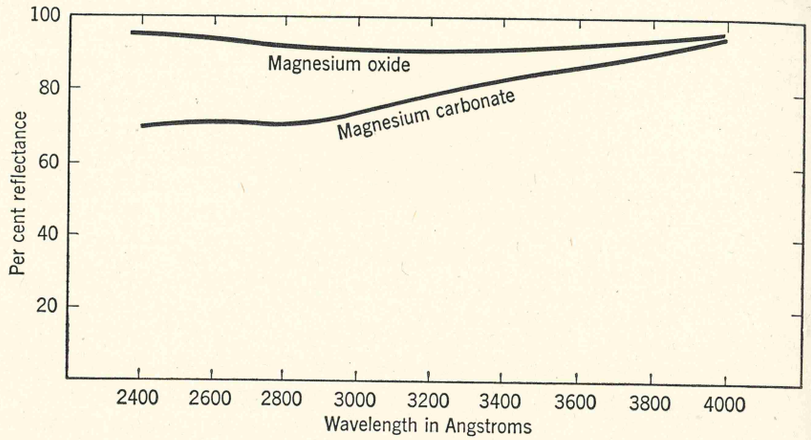

FIG. 16. Reflection from magnesium oxide and magnesium carbonate. (F. Benford, S. Schwartz, and G. Lloyd, *J. Optical Soc. Am.*, **38**, 964, 1948.)

by the desired film properties, as too high a pigment content results in a brittle inelastic film.

The addition of a small amount of colored pigment to a white paint may result in a large decrease in the ultraviolet reflection. The reflectance decreases with increase in volume per cent of colored pigment added.

Table 4 gives the absorption coefficient in the region around 3024 A for some of the commonly used oils, resins, plasticizers, thinners, and driers. Only materials with an absorption coefficient of less than 60–70 in.$^{-1}$ (23.6–27.6 cm^{-1}) are satisfactory for ultraviolet paints. The table shows that the natural resins absorb too strongly, but that many of the synthetic resins are suitable. Drying oils and driers cannot be used. Several plasticizers are satisfactory. Of course, other factors such as stability and the character of the film formed must be considered in the choice of materials. For example, nitrocellulose is unsatisfactory in

TABLE 4

ULTRAVIOLET ABSORPTION COEFFICIENTS *

Material	% Soln. Tested	Absorption Coefficient,† Inches^{-1}
A. Oils		
Oiticica	....	$> 2.5 \times 10^2$
Tung	....	1.6×10^2
Heat-bodied linseed	....	1.6×10^2
Refined perilla	....	1.6×10^2
Alkali-refined linseed	....	1.5×10^2
Heat-bodied perilla	....	1.5×10^2
Special dehydrated castor	....	1.2×10^2
Alkali-refined soybean	....	1.2×10^2
Dehydrated castor	....	95
Commercial castor	....	74
Refined castor	....	62
B. Resins		
Modified phenolic (B. R. 2963 Bakelite)	20	1.4×10^2
Modified phenolic (Amberol F7 light)	20	1.4×10^3
Maleic-rosin ester (801 Amberol)	20	1.3×10^3
Limed rosin	20	1.3×10^3
V-13005 light stable phenolic	67	1.3×10^3
Kopol 500 (fused Congo-glycerol ester)	20	1.2×10^3
Ester gum A. V. 5–7	20	1.1×10^3
Terpene resin (550 Durez)	20	9.6×10^2
Light stable phenolic (XR4036 Bakelite)	20	8.8×10^2
100% phenolic (XR820 Bakelite)	20	8.1×10^2
100% phenolic (2000 Super Beckacite)	20	6.8×10^2
Cumar W ½	20	6.3×10^2
Batavia dammar	20	5.8×10^2
100% phenolic, heat-reactive (Varcum 250-F)	20	5.3×10^2
4X Manila	20	4.5×10^2
Hydrocarbon resin (Nevillite)	20	2.3×10^2
Glyceryl phthalate varnish B	65	2.2×10^2
Glyceryl phthalate varnish A	65	1.7×10^2
Glyceryl phthalate varnish C	65	1.4×10^2
Ethylcellulose B (Hercules)	10	75
Urea-formaldehyde (Beetle 227–8)	50	64
Urea-formaldehyde, soln. A	50	52
Methyl methacrylate	18	48.8
Urea-formaldehyde	Pure	46
Ethyl methacrylate	20	40.5
Nitrocellulose lacquer	25	40 ‡
Acryloid B-7 (methacrylates)	20	30
Urea-formaldehyde, soln. B	50	25
Propyl methacrylate	20	24.8
Butyl methacrylate	20	21.8
Isobutyl methacrylate	20	20.0
Vinylite AY-AA	18	20

TABLE 4 (*Continued*)

ULTRAVIOLET ABSORPTION COEFFICIENTS

Material	% Soln. Tested	Absorption Coefficient,† Inches^{-1}
C. Plasticizers		
4,4′-Dichlorodiphenyl	4.5	1.9×10^3
Methyl abietate	Pure	2.3×10^2
Hydrogenated methyl abietate	Pure	1.6×10^2
Di-(*o*-xenyl)monophenyl phosphate (Dow plasticizer 6)	Pure	1.2×10^2
Diphenyl mono-(*o*-xenyl) phosphate (Dow plasticizer 5)	Pure	1.2×10^2
Benzyl benzoate	Pure	1.2×10^2
Methyl ricinoleate	Pure	1.0×10^2
Santicizer 8	Pure	60
Dibutyl phthalate	Pure	49
Santicizer B-16	Pure	37
Butyl stearate	Pure	37
Tricresyl phosphate	Pure	30
Triphenyl phosphate	50	20
Di-(*p-tert*-butylphenyl) monophenyl phosphate (Dow plasticizer 2)	Pure	18
n-Butyl-*d*-tartrate	Pure	15
Tri-(*p-tert*-butylphenyl) phosphate (Dow plasticizer 7)	41	8.1
Tripropionin	Pure	2.8
D. Thinners, Driers, and Other Liquids		
6% cobalt Nuodex	....	$> 2.5 \times 10^2$
6% manganese Nuodex	....	$> 2.5 \times 10^2$
24% lead Nuodex	....	1.7×10^2
Acetone	....	1.2×10^2
Sulfate wood turpentine	....	76
Casein soln.	....	57
Mineral spirits	....	44
Solvesso 2	....	28
Commercial xylene	....	24
Toluene	....	9.5
Butanol	....	9.2
Ethylene dichloride	....	3.9
Glycerol	....	3.5
Absolute alcohol	....	1.1
Distilled water	....	0.4

* D. F. Wilcock, W. Soller, *Ind. Eng. Chem.*, **32,** 1449 (1940).

† Absorption coefficient is a quantity independent of the sample thickness, d, and is related to the transmission by the relation $k = -(1/d) \ln t$.

‡ In solution.

spite of its low absorption because it deteriorates on exposure to ultraviolet.

Paints may undergo considerable change in ultraviolet reflectance with time.

REFLECTION OF SKIN

The human skin has a very low reflection for ultraviolet. Table 5 gives the values for the reflection coefficient of the average untanned skin of white persons.

TABLE 5

REFLECTION COEFFICIENT OF HUMAN SKIN *

Wavelength in Angstroms	Per Cent Reflection
2400	3
2600	4
2800	4
3000	5
3200	11
3400	16
3600	21
4000	28
4500	35
5000	42
5500	48
6000	54
6500	65
7000	68

* M. Luckiesh, L. L. Holladay, and A. H. Taylor, *J. Optical Soc. Am.*, **20,** 423 (1930).

Although the reflection of the tanned skin is less than that of the untanned skin for visible radiation, there is little difference in the ultraviolet. Detailed studies of the shape of the reflectance curve of the skin have shown the presence of the pigments, oxyhemoglobin, reduced hemoglobin, carotene, malanin, melanoid, and vitamin A.

The difference in reflection between the skin of a colored and a white person is much less in the ultraviolet than in the visible. No pigments have been found in the Colored races additional to those found in the Caucasian race.

REFLECTION FILTERS

Reflection-type interference filters consist of a reflecting surface covered with a thin layer of a transparent medium on top of which is a

semi-transparent metal surface. For a certain critical wavelength, the phase difference between the energy reflected from the top and the bottom surfaces is 360°, so that the two are in phase. All other wavelengths produce interference between the two surfaces. A very satisfactory filter of this type can be made for the selective reflection of

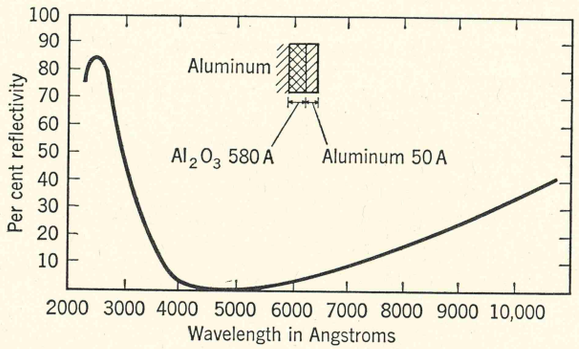

FIG. 17. Reflectivity of reflection type of interference filter. (G. Hass, *J. Optical Soc. Am.*, **39**, 539, 1949.)

2537 A radiation by coating an aluminum surface with a thin hard layer of oxide by anodic oxidation in an electrolyte such as ammonium tartrate. This coating exhibits no noticeable absorption in the ultraviolet, visible, and infrared. This layer is formed to a thickness of 585 A. On top of it is deposited by evaporation a semi-transparent film of aluminum 50 A thick. The reflectivity of this filter as a function of wavelength is shown in Fig. 17. The visible reflectivity is reduced to less than 20 per cent, whereas the reflectivity in the ultraviolet at 2537 A is about 85 per cent.[6] Reflection filters are sensitive to the angle of incidence and are correct only at a particular value of angle of incidence.

TABLE 6

REFLECTION OF 3000 A ULTRAVIOLET FROM THE GROUND

Surface	Per Cent Reflection *
Fresh snow	85
Dry dune sand	17
Sandy turf	2.5
Water	5

* K. Buttner and E. Sutter, *Strahlentherapie*, **54**, 156 (1935).

REFLECTION FROM GROUND

The reflection from the ground under various conditions is shown in Table 6.

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2. G. B. Sabine, *Phys. Rev.*, **55**, 1066 (1939).
3. G. Hass and N. W. Scott, *J. Optical Soc. Am.*, **39**, 180 (1949).
4. G. F. Stutz, *J. Franklin Inst.*, **200**, 93 (1925).
5. F. Benford, S. Schwarz, and G. Lloyd, *J. Optical Soc. Am.*, **38**, 964 (1948).
6. Georg Hass, *J. Optical Soc. Am.*, **39**, 539 (1949).

7 Some Applications and Effects of Ultraviolet

Although there are numerous technical applications for ultraviolet radiation, the most familiar application is in therapy. The benefits of natural solar ultraviolet, of course, have been realized (though perhaps not explicitly) since time immemorial. The scientific basis for the use of artificial ultraviolet in therapy, that is, ultraviolet from sources other than the sun dates from the discovery by N. R. Finsen in 1899 that it is the ultraviolet component of sunlight which is responsible for sunburn. This discovery led to widespread study of the effects of ultraviolet.

Finsen, a Dane, who was himself an invalid, received the Nobel Prize in 1903 for his pioneer work in ultraviolet therapy.

Ultraviolet has been extensively used in the treatment of various forms of tuberculosis, to promote the healing of wounds, in various skin diseases, to prevent and cure rickets, to prevent the spread of airborne infection, and for general prophylaxis. It has also been used to make up for the lack of solar ultraviolet received by factory workers, miners, and school children. The Germans provided ultraviolet treatment for their troops in Norway during World War II to make up for the lack of sunlight during the polar night. Similarly it has been used in submarines.

Many of the therapeutic applications are still the subject of considerable controversy. Some of the beneficial results have a sound physical basis. Some may be partly psychological. In some cases the cosmetic effect is sufficient justification. Even where there is agreement as to the results, the modus operandi is still in question. The whole subject is one in which much work remains to be done. In only a few areas of the biological field is the application of ultraviolet on a reasonably satisfactory quantitative basis. These are the production of erythema, the prevention and cure of rickets, and the killing of bacteria and molds. With respect to these effects there exists a considerable amount of quan-

titative data relating the effect to the amount of energy and the wavelength, and workers in the field are in substantial agreement.

Erythema

A few hours after exposure to ultraviolet there results a reddening of the skin called erythema or, more commonly, sunburn. It ordinarily appears in 1 to 6 hr after exposure and disappears gradually in 1 to 3 days. Erythema is to be distinguished from hyperemia, a reddening due to temporary excess of blood in the network of small vessels in the skin. The latter is produced rapidly by visible and infrared energy in sufficient intensity and disappears soon after the irradiation.

The intensity of erythema depends upon the exposure. A just perceptible erythema, called a minimum perceptible erythema, or MPE, is used as a convenient measure of ultraviolet dosage. (An MPE disappears in 24 hr.) Greater exposure results in various degrees of inflammation or even blistering and hemorrhage. The histology and etiology have been studied in considerable detail, but the phenomena are quite complex and are not thoroughly understood. It is known, however, that histamine or histamine-like substances are formed in the skin. Erythema is followed by a pigmentation or tanning of the skin which becomes noticeable two or three days after irradiation.

The relation between wavelength and erythemal effectiveness was first established by Hausser and Vahle. Others have since confirmed their work, and there is now general agreement on this relation. The erythema curve is shown in Fig. 1. This curve represents the relative effectiveness of equal amounts of energy at different wavelengths in producing erythema. From the curve it can be seen that the most effective wavelength is about 2967 A. Wavelengths around 2500 A are also very effective, the region between being less effective. Almost no erythema is produced by wavelengths longer than 3200 A. The values differ for different individuals and, of course, depend upon previous exposure. Figure 1 is for the average untanned skin. The curve taken from the data of Luckiesh shows higher values in the region 2400–2800 A than the one adopted by the International Commission on Illumination, but the results are probably more representative. All observers are in good agreement on the region between 2800 and 3200 A.

By means of this curve it is possible to express the effectiveness of a given amount of energy at any wavelength in terms of the amount of energy of 2967 A which would have the same erythemal effect. If the energy distribution of any source of ultraviolet is known, its erythemal effectiveness may be calculated by multiplying the values of energy in

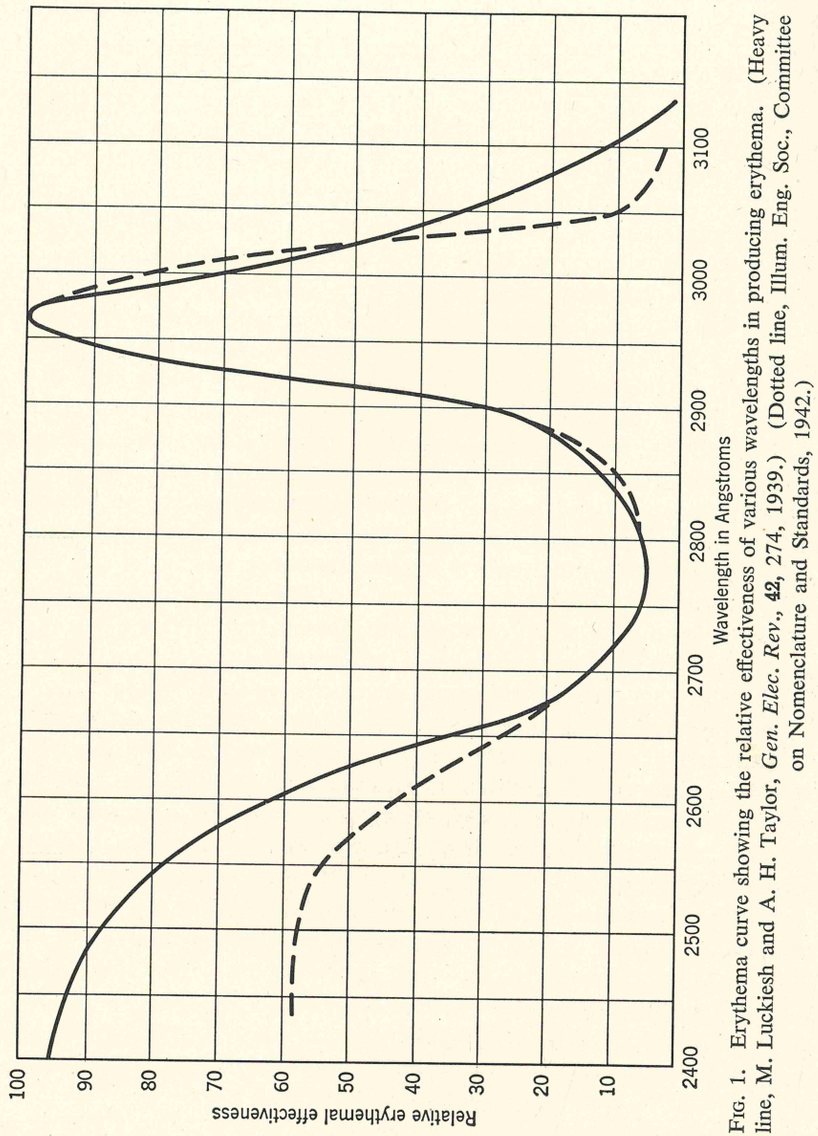


FIG. 1. Erythema curve showing the relative effectiveness of various wavelengths in producing erythema. (Heavy line, M. Luckiesh and A. H. Taylor, *Gen. Elec. Rev.*, **42**, 274, 1939.) (Dotted line, Illum. Eng. Soc., Committee on Nomenclature and Standards, 1942.)

each wavelength region by the corresponding ordinate of the erythema curve and taking the sum of all of these values. This will be the equivalent amount of energy at 2967 A which would have the same effect as the source under consideration.

Minimum perceptible erythema is produced by 250,000 ergs per cm^2 of 2967 A. This is equivalent to 25,000 μw-sec per cm^2 of 2967 A or its erythemal equivalent.

The type of erythema produced depends somewhat on the wavelength. The erythema produced by the longer wavelengths develops more slowly and disappears more slowly than that produced by shorter wavelengths. The erythema produced by wavelengths shorter than 2700 A is of a more superficial character than that produced by the longer wavelengths. This may be owing to the fact that the penetration of the shorter wavelengths into the skin is less.

The latent period for erythema produced by solar radiation is somewhat less than for erythema produced by the mercury arc.[1] The former increases relatively rapidly after exposure and reaches its maximum in 5–6 hr. The erythema produced by the mercury arcs shows a latent period of 2–3 hours after which it increases gradually to its maximum in about 9 hr.

The relation between the degree of erythema and the intensity of irradiation depends upon the wavelength. Equal multiples of the threshold dose at different wavelengths do not produce equal degrees of erythema. The degree of erythema increases much more rapidly with increase in dose of the longer than of the shorter wavelengths. Thus Hausser and Vahle found that a very small increase in exposure to 3020 A over that required to produce MPE resulted in a more severe erythema than an exposure of several times the threshold value for 2537 A. Thus an exposure of several times the threshold value of solar radiation will produce more severe burns than a similar overexposure to a germicidal lamp which radiates only in the shorter wavelengths. The extent to which the degree of erythema increases with dose roughly parallels the ratio of the energy between 2800–3150 A to that between 2400–2800 A.

The degree of erythema produced by exposure to midsummer noonday sun in terms of the dose which produces MPE is as follows:

Relative Exposure Time	Degree of Erythema
1	MPE
2.5	Vivid, producing moderate tan
5	Painful "burn"
10	Blistering

Exposure Limits

The Council on Physical Medicine and Rehabilitation of the American Medical Association has set limits of exposure tolerance for various exposure times for installations of germicidal lamps. These are as follows:

Continuous exposure	0.1 μw per cm^2
Less than 7 hr exposure per day	0.5 μw per cm^2

Erythemal Effectiveness of Various Sources

The approximate exposure required to produce MPE on the average untanned skin by average midday midsummer sunlight and by various artificial sources, in efficient reflectors at a distance of 24 in. from the skin, is given in the accompanying table.

	Minutes *
Summer sunlight	20
Type S1, 400 watt	4
Type S4, 100 watt	5
Type RS4, 100 watt	18
Type RS, 275 watt	6
F-sunlamp, 40 watt	8
Quartz mercury arc, 360 watt	3
Tungsten CX, 500 watt	50
Germicidal, 4 watt	8
Germicidal, 8 watt	5
Germicidal, 15 watt	2.7
Germicidal, 30 watt	0.7
Type AH-6, 774 glass, 1000 watt	0.2
Type AH-6, quartz, 1000 watt	0.05

* M. Luckiesh, *Applications of Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., Inc., New York.

Pigmentation (Tanning)

Another consequence of exposure to ultraviolet in addition to erythema is the pigmentation of the skin generally known as tanning. This becomes noticeable about 48 hr after exposure and increases gradually for several days. Tanning is in part due to the migration of the pigment already present in the basal cells to more superficial layers and in part due to the formation of new pigment. The former process takes place first, then the latter. The tanning response curve appears to follow the erythema curve in a general way. The type of tanning, however, appears to vary with the wavelength, being a deeper brown when produced by the longer wavelengths and somewhat more yellowish when produced by the shorter wavelengths.

There is a distinction between the ordinary tanning which is subsequent to erythema and another kind of tanning which follows immediately after irradiation without previous or accompanying erythema. These two kinds of tanning are due to fundamentally different skin reactions. This second kind of tanning is known as direct pigmentation. In contrast to erythema the direct pigmentation is produced by long-wave ultraviolet, wavelengths greater than 3200 A. The intensity of radiation required to produce this kind of pigmentation is about 500- to 800-fold the intensity required for erythema. Accordingly, this effect is one which is of little practical importance in using any of the currently available light sources, since a strong burn due to the shorter wavelengths would result long before any pigmentation by the longer wavelengths. The solar spectrum, however, differs from that of artificial sources in having a relatively large proportion of its radiation in the 3200–4000 A region in comparison with the energy below 3200 A. Hence, according to Henschke and Schulze, it is possible to get minimum perceptible pigmentation in the summer by exposure to the sun in one-third of the time required for MPE.

There is no known relation between tan and health. Pigment formation and therapeutic benefits are independent phenomena.

Ultraviolet also produces effects on the composition of the blood, the circulation, and the metabolism too involved for discussion here.

The skin (untanned) appears to be less sensitive to ultraviolet in the summer than in the winter. Redheads and blondes are most sensitive, but otherwise there is no close correlation between eye and skin color and sensitivity. The role of dampness of the skin is somewhat obscure. Perspiration absorbs ultraviolet radiation.[2] However, greater penetration of ultraviolet into moist skin may also be a factor to be considered.[3]

At low temperatures the sensitivity of the skin to erythema is decreased.[4] Tests made with artificial ultraviolet show that erythema is affected by the simultaneous irradiation of the skin with infrared radiation. The result of the infrared in most cases is to reduce the erythemal threshold and to decrease the latent period.

The basis for the use of sun-tan creams and oils is to absorb the shorter wavelengths and permit the passage of the longer wavelengths. Thus advantage is taken of the direct pigmentation of the longer wavelengths and the production of erythema by the shorter wavelengths is reduced to a minimum. For the transmission of these substances, see Chapter 5. Obviously, although these sun-tan preparations facilitate the acquiring of a tan and make possible long exposures without erythema, they do not in any way accelerate the process.

Conjunctivitis

Exposure of the eyes to ultraviolet radiation results in conjunctivitis, a painful inflammation of the membrane of the eye. The effectiveness of ultraviolet in producing conjunctivitis is somewhat different from that for erythema. Radiation of wavelength less than 2800 A is more effective in production of conjunctivitis than erythema. This is probably because of the absence of the strongly absorbing horny layer in the conjunctiva. Experiments [5] indicate that the conjunctivitis curve is similar to the absorption curve of nucleic acid. Radiation of wavelengths longer than 320 mm of intensity greater than any which can be obtained in nature except by looking directly into the sun have been shown to have no deleterious effect on the light sensitivity of the eye.[6]

Ultraviolet in the Prevention and Cure of Rickets

Rickets is a disturbance of the growing organism of such a nature that lime salts no longer deposit in the bones. This results in imperfect calcification so that the bones do not become sufficiently rigid to support their normal stresses and deformation results. It is now known that vitamin D is necessary to promote the healthy growth of bone. Cod liver oil is one of the richest sources of vitamin D and has long been used as a preventive and cure for rickets.

Although it had been known for some time that sunlight was important in the therapy of this disease, it was not till 1919 that Huldschinsky showed conclusively by means of X-rays of bony structures that exposure to a mercury arc cured rickets in infants. A few years later Hess and his coworkers showed that rickets could be cured by sunlight. It is now known that ultraviolet converts some of the sterols in the skin to vitamin D which is then absorbed by the system.

The quantitative aspects of the treatment of rickets by ultraviolet are fairly well established, and the amount of ultraviolet necessary to prevent and to cure rickets is known. The antirachitic efficiency of radiation as a function of wavelength is shown in Fig. 2. This curve shows the relative efficiency of energy of different wavelengths in curing rickets. It was determined by experiments on rats, but the same relations have been shown to hold for humans. The curve shows a maximum at 2800 A and a long-wave limit at 3130 A. That is, wavelengths greater than 3130 A are ineffective in curing rickets. It can be seen by comparing this curve with the erythemal effectiveness curve of Fig. 1 that the long-wave limit for both is approximately the same. Otherwise there is a marked difference between the two. The maximum in the

antirachitic curve at 2800 A comes just where the minimum occurs in the erythema curve. Accordingly, a measurement of erythemal effectiveness is not necessarily an index to the effectiveness of ultraviolet in the case of rickets. In practice, however, at least in the case of mercury arcs, erythema may be a fairly good guide because in these lamps the

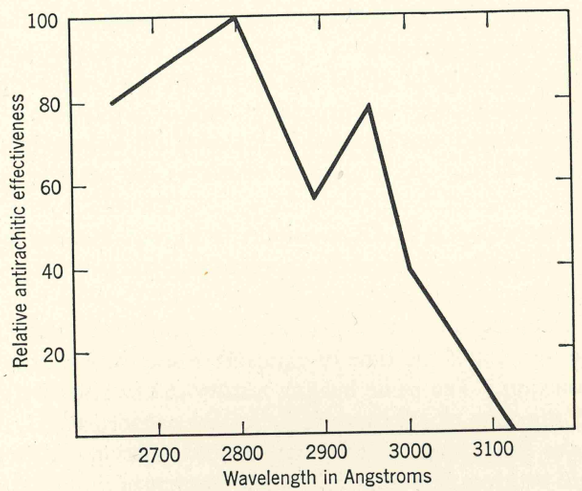


Fig. 2. The spectral antirachitic curve showing the relative effectiveness of different wavelengths in preventing and curing rickets. (A. Knudson and F. Benford, *J. Biol. Chem.*, **124**, 287, 1938.)

energy between the wavelengths 2576 A and 2925 A is relatively small compared with the energy at slightly shorter and slightly longer wavelengths. Bunker and Harris [7] measured the total amount of energy required at various wavelengths to cure rickets in rats. Their values are given below:

Angstroms	Energy in Ergs
2537	775,000
2652	660,000
2804	600,000
2967	420,000
3025	900,000

It has been shown that spring and summer sunshine possesses much greater antirachitic effect than winter sunshine. This is owing to the fact that the only portion of the solar spectrum effective in preventing rickets is the very narrow region between 2900 A and 3130 A. In

winter (see Chapter 4), the amount of energy in this region is greatly reduced by the increased air mass as well as by the smoke and dust of cities. In many cities the intensity of ultraviolet radiation in winter is not enough to prevent rickets. In Toronto [8] over a period of 3 years it was found that solar radiation from the latter part of October through the first part of February produced a slight but definite antirachitic effect. This effect increased sharply about February 15 and continued at about 8 times the winter level. The change is apparently largely dependent upon the altitude of the sun above the horizon and the consequently decreased air mass. The critical angle is about 35°. The effect is not so much due to the increase in intensity in summer of the wavelengths present during the winter but rather to the presence of shorter wavelengths.

Experiments with rats in Albany similarly showed that the antirachitic effect of midsummer sunshine was approximately 10 times as great as that of midwinter sunshine.

The reciprocity relation has been found to apply to the cure of rickets.[9] That is, the product of the time of exposure times the intensity of exposure is a constant. The same healing results at low intensity as at high intensity, if the time of exposure is increased proportionately, and vice versa. It was found that the total amount of radiation required to cure rickets could be given in a relatively small number of doses. This radiation did not have to be applied to the entire body but could be applied to a relatively small area. The amount of exposure required to cure rickets is several times as much as that required to prevent the disease.

Production of Vitamin D

In 1924 Steenbock and Black, and Hess showed almost simultaneously that many substances acquired antirachitic properties by irradiation. A partial list of these substances is: olive oil, linseed oil, lanolin, cottonseed oil, corn oil, bean oil, nut sterol, cholesterol, phytosterol, skin, dextrin, casein, wheat, wheat flour, milk, milk powder, hay, chicken mash, spinach, lettuce, orange juice, sawdust, yeast, rolled oats, farina, patent flour, shredded wheat biscuit, whole corn meal, corn flakes, and hominy. Their one common denominator is the presence of unsaponified fats. The effect of ultraviolet is to convert some of the sterols present into vitamin D. This reaction has been studied by many experimenters.

It has been shown [10] that the rate of production of vitamin D from ergosterol is proportional to the first power of the light intensity. The vitamin D also absorbs in the same wavelength region as that which

forms it, and it is destroyed by this radiation. The highest concentration of vitamin D which can be formed by direct irradiation of ergosterol is 35 per cent.

The international unit of vitamin D potency is defined in terms of the calcification produced in rats under certain specified standard conditions of feeding. One international unit of vitamin D is synthesized from ergosterol when 900 ergs of ultraviolet energy within the synthesizing region (249–313 μ) are absorbed.

Various foodstuffs are irradiated commercially in order to increase their vitamin D potency. The irradiation of milk is complicated by the fact that irradiation also produces undesirable flavors in the milk. This flavor is definitely associated with the protein fraction of milk. (Objectionable flavor is also produced by the action of ozone.) Radiation of shorter wavelengths than 3100 A is most effective in producing flavor, and the production of flavor increases with decreasing wavelength.

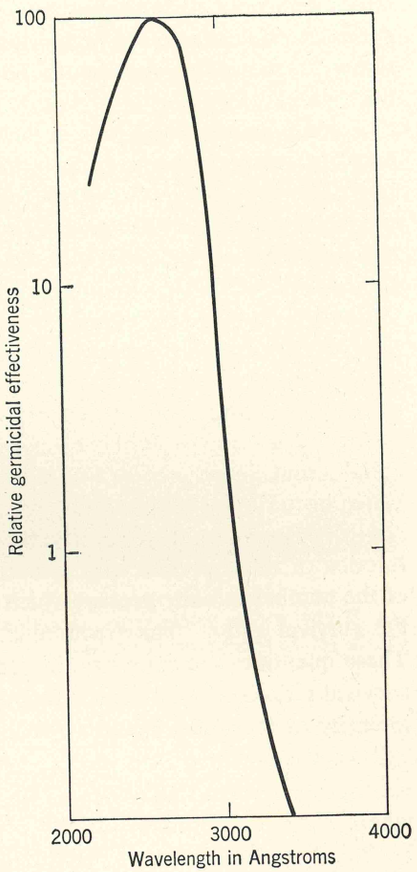


Fig. 3. The bactericidal effectiveness curve showing the relative effectiveness of various wavelengths in killing bacteria. (M. Luckiesh, *Germicidal, Erythemal and Infrared Energy*, D. Van Nostrand Co., New York, 1946.)

Germicidal Effects

The bactericidal action of sunlight was discovered by the Englishmen Downes and Blunt in 1877. Since their pioneer work the effect of radiation on bacteria has been studied in detail, and the relation between lethal action and wavelength and energy is now well known. The relation between bactericidal effect and wavelength is shown by the curve of Fig. 3 where the relative bactericidal effect is plotted as a function of wavelength.

This curve has a maximum at 2600 A and falls practically to 0 at 3200 A. Luckiesh has extended the curve beyond 3200 A and has shown that the effectiveness at 3200 A is 0.4 per cent of the peak value and at 7000 A 0.002 per cent. In a general way this curve resembles the absorption curve for nucleic acid.[11] Within the limits of experimental accuracy the shape of the curve appears to be independent of the nature of the bacteria.

A consequence of the peak in the curve at 2600 A is that low-pressure mercury vapor lamps with their high output at 2537 A, close to this peak, are very efficient bactericidal agents. Since 90 per cent of the output of visible and ultraviolet radiation from these lamps is concentrated in this one line, which is close to the point of maximum bactericidal effectiveness, the remainder of the radiation may be neglected. For sources having a wider energy distribution the spectral energy distribution curve may be used to calculate the germicidal effectiveness, namely the equivalent energy at 2600 A which would produce the same effect as the distribution in question.

An understanding of the behavior of bacteria in the presence of a lethal agent is necessary before discussing the action of ultraviolet. When bacteria are subjected to any lethal agent, such as heat, disinfectants, X-rays, and ultraviolet, they do not all die at once, but a constant fraction of those present dies in each increment of time. The fraction of the number initially present which survives at any given time is called the survival ratio. The fraction killed is 1 minus the survival ratio. These quantities are expressed in per cent by multiplying by 100. The survival ratio is an exponential function of the time of exposure and the intensity of the lethal agent. For ultraviolet, it takes the form:

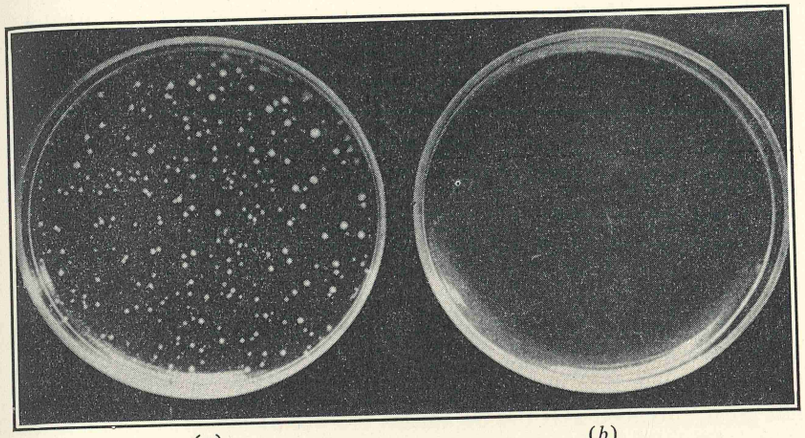
$$N/N_0 = e^{-kIt}$$

where N_0 = the number initially present.
N = the number surviving at time t.
t = the time of exposure to the lethal agent.
k = a constant.
I = the intensity of the lethal agent.

The effectiveness of the lethal agent is accordingly expressed in terms of the dose required to produce a given survival ratio. In killing by ultraviolet radiation, I = intensity of radiation in microwatts per square centimeter, k is a constant depending upon the nature of the organism and the wavelength of the radiation.

An exposure $I \times t = 1/k$ reduces the exponent of e to -1, and the

corresponding survival ratio is $1/e = 0.368$. The exposure required to give a survival ratio of 0.368 is called the mean lethal dose, lethal exposure, or inactivation dose. (A kill of 63 per cent has been termed a lethe by Wells.[12]) As the amount of energy required for a unit lethal exposure depends not only upon the nature of the organism but also upon other factors such as humidity, this unit is rather a variable quantity. It appears most convenient to state the exposure in microwatt minutes for



(*a*) (*b*)

FIG. 4. Killing of bacteria by 2537 A radiation. Agar plates seeded with *B. coli* and incubated for 24 hr. *a*. Control. *b*. Exposed to 15-watt lamp at 7½ in. for 30 sec.

a given survival ratio. Since a plot of N/N_0 vs. exposure It is a straight line on semi-log paper, the line is fixed by the two points corresponding to 0.368 survival ratio for unit lethal exposure and 1.0 survival ratio for zero exposure.

The test of whether a bacterium has been killed (or rendered inactive) is its ability to reproduce itself and form colonies when placed in a suitable culture medium. Figure 4 shows a Petri dish in which 1 cc of a very dilute suspension of bacteria has been poured over the surface of the nutrient agar. This suspension was so dilute that the individual bacteria in it were widely scattered over the surface. After a 24-hr period of incubation each original organism has reproduced manyfold and formed a colony which is visible to the naked eye. This is a measure of the number of bacteria present in the original cubic centimeter of suspension. The second plate is identical with the first except

that after inoculating the plate with bacteria it was exposed to a 15-watt germicidal lamp at a distance of 7½ in. for ½ min. It was then incubated under the same conditions as the first plate. The much smaller number of colonies formed is an indication of the lethal action of the ultraviolet. From actual counts of the number of colonies on plates after various periods of exposure the survival ratio may be obtained. Figure 5 is a plot of the equation for the case of *Bacillus coli* on the surface of agar.

The exposure is the product of the intensity of radiation and the time. Within wide limits the Bunsen-Roscoe reciprocity law applies to the killing of bacteria. That is, a given exposure results in a given survival ratio, regardless of whether the exposure consists of a low intensity for a long time or a high intensity for a correspondingly shorter time. For both bacteria and mold spores this law has been found to apply over a thousandfold range in intensity.[13] The failure of the law at very low intensities is probably because the exposure time becomes so long that bacteria reproduce during the time of exposure and the effect on a single individual becomes obscured.

Temperature has little if any effect on the bactericidal effect of radiation between 5 and 37°C.

The differences in sensitivity between different kinds of bacteria are not great, provided that the organisms are not of the spore-forming variety. Measurements made by Sharp on eight different kinds of organisms, including several pathogens, did not show any greater than a twofold difference in sensitivity between different species. Table 1 shows the intensity required to inhibit colony formation in 90 per cent of the organisms for a number of different kinds of organisms, compiled by Hollaender from the work of a number of different investigators. The table probably involves considerable differences in technique and measurement procedure. In spite of this the variation in intensity required is remarkably small.

Spore-forming bacteria are much more resistant than nonspore formers. For example, *B. subtilis,* which is a spore former, is about 5–10 times as resistant as *B. coli.*

Molds and yeast are considerably more resistant than bacteria. This difference in resistivity covers a range from 100 to 1000.

The mechanism of the inactivation of bacteria by ultraviolet is not clearly understood. Although first regarded as actual killing of the organism, it is now thought to be a process which prevents the multiplication of the cells so that normal dying off occurs before multiplication has taken place.[14]

TABLE 1 *

INCIDENT ENERGIES AT 2537 A IN ERGS PER SQUARE CENTIMETER NECESSARY TO INHIBIT COLONY FORMATION IN 90 PER CENT OF THE ORGANISMS

Organism	Energy
Bacillus anthracis	452×10^2
B. megatherium sp. (veg.)	113
B. megatherium sp. (spores)	273
B. paratyphosus (aver. of 3 strains)	320
B. subtilis (mixed)	710
	600
B. subtilis (spores)	1200
Corynebacterium diphtheriae	337
Dysentery facilli (aver. of 5 strains)	220
Eberthella typhosa	214
Escherichia coli	300
Micrococcus candidus	605
M. piltonensis	810
M. sphaeroides	1000
Neisseria catarrhalis	440
Phytomonas tumefaciens	440
Proteus vulgaris	264
Pseudomonas aerugenosa	550
Ps. fluorescens	350
Salmonella enteritidis	400
S. typhimurium (aver. of 3 strains)	800
Sarcina lutea	1970
Serratia marcescens	242
	220
Shigilla paradysenteriae	168
Spirillum rubsum	440
Staphylococcus albus	184
	330
	184
Staph. aureus	218
	260
	495
Streptococcus hemolyticus	216
Strep. lactis	615
Strep. viridans	200

* *Aerobiology,* A.A.A.S., Publication No. 17 (1942).

VIRUSES

The resistance of many viruses is comparable with that of bacteria. Influenza virus, vaccine virus, and bacteriophage have inactivation curves resembling absorption spectra of nucleoproteins, having a maximum in the curve at 2650 A. Tobacco mosaic is much more resistant

than bacteria (about 200 times), and its sensitivity curve decreases from 2250 A to 3100 A with only a slight maximum at 2600 A.[15]

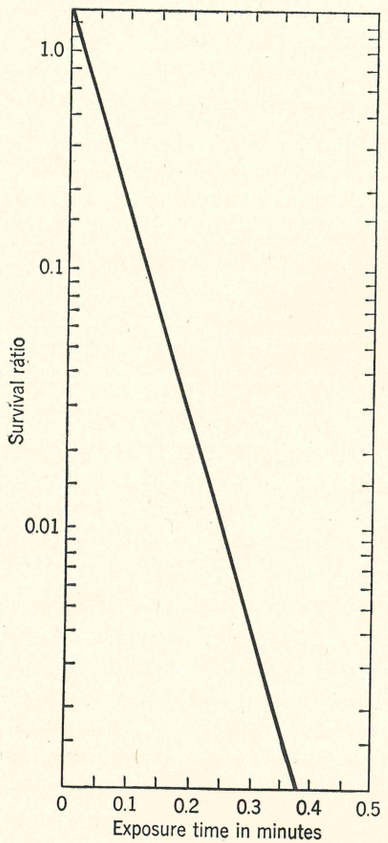


FIG. 5. Survival ratio as a function of exposure time for *B. coli* exposed to 100 μw per cm^2 of 2537 A radiation.

OTHER ORGANISMS

A sufficiently high intensity of radiation will kill small insects. Hollaender studied the effect of ultraviolet on the eggs of the common pinworm.[11] The incident energy required per unit area for 90 per cent killing is about 10 times as great as for *B. coli*. The inactivation curve for pinworm eggs shows that they are most sensitive to the shortest wavelength used in these experiments, 2280 A, and the curve falls to about 10 per cent at 2950 A with only a very slight maximum at 2800 A. This curve which is quite different from the curve for bacteria resembles a protein absorption curve. Because of the conditions under which pinworm eggs are found, protected by dirt and dust, control of them by ultraviolet radiation does not appear promising.[16]

The ultraviolet from low-pressure mercury vapor lamps was found to be quite effective in killing thermophilic organisms in sugar.[17] It is necessary for the sugar to be in a thin layer and to be agitated in order to make sure that all the organisms are exposed to the radiation.

Ultraviolet also produces sublethal effects on bacteria, fungi, and molds. These effects include mutations, morphological changes, changes in rate of growth, and delayed lethal effects. Bacteria which survive irradiation show increased response to adverse conditions in comparison with normal bacteria. They are more easily killed by mild disinfecting agents and show increased sensitivity to heat.

Although the degree of killing resulting from ultraviolet exposure does not vary greatly from one species to another, it depends greatly on the conditions of irradiation. The moisture conditions exert a very marked effect. Where the bacteria are suspended in air an increase in relative humidity results in a greatly decreased death rate. This effect is most noticeable at humidities greater than about 50 per cent. In one experiment reported by Luckiesh, increasing the relative humidity from 23 to 75 per cent increased the survival from 6.5 to 24 per cent. Similarly, bacteria suspended in a liquid medium are much more resistant than those suspended in air, even after making allowance for the absorption of the medium.

Table 2 gives the amount of ultraviolet energy of wavelength 2537 A

TABLE 2

EXPOSURE REQUIRED TO KILL VARIOUS KINDS OF ORGANISMS

Organism	Survival Ratio	Exposure in μw-sec/cm^2
Fungi	0.0001	192,000
	0.01	96,000
	0.1	48,000
Spore formers and *B. coli* in water	0.0001	24,000
	0.01	12,000
	0.1	6,000
B. coli (dry) and viruses	0.0001	3,000
	0.01	1,500
	0.1	750

required to kill bacteria and molds. The data apply to *B. coli* specifically because this is a convenient test organism to use, but the figures apply almost as well to other nonspore-forming organisms. Figure 6 shows the required ultraviolet intensity as a function of exposure time to give the survival ratios shown in the table.

For all practical purposes, bacteria on moist surfaces (such as culture medium) require the same exposure as those in water or at high humidity in air.

Since 2537 A is strongly absorbed by many organic media, a very thin layer covering bacteria is sufficient to afford them considerable protection. Accordingly, in any application to the killing of bacteria it is important to make sure that the organisms are really exposed and are not covered by a protecting layer.

It has been shown [18] that the survival ratio of certain bacteria (conidia

of actinomycetes, *S. griseus*) is increased if the irradiated cells are stored in the light instead of in the dark.

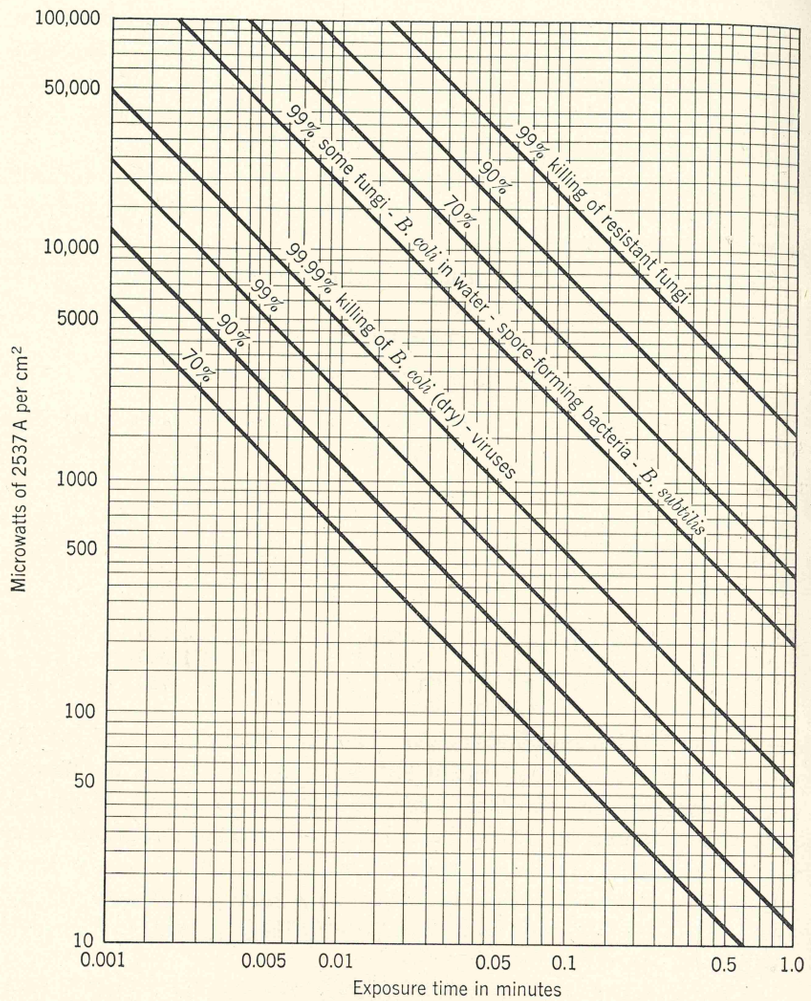


FIG. 6. Ultraviolet intensity and exposure time required to give various values of survival ratios for bacteria and molds. (*Gen. Elec. Lamp Bulletin* LD-14.)

APPLICATIONS OF GERMICIDAL EFFECT

The applications of the germicidal effects of ultraviolet fall into two broad classes: killing of organisms on surfaces and killing of organisms

suspended in air or in a liquid medium. The first class includes the protection of many food and pharmaceutical products during their processing and packaging. The products themselves and their containers,

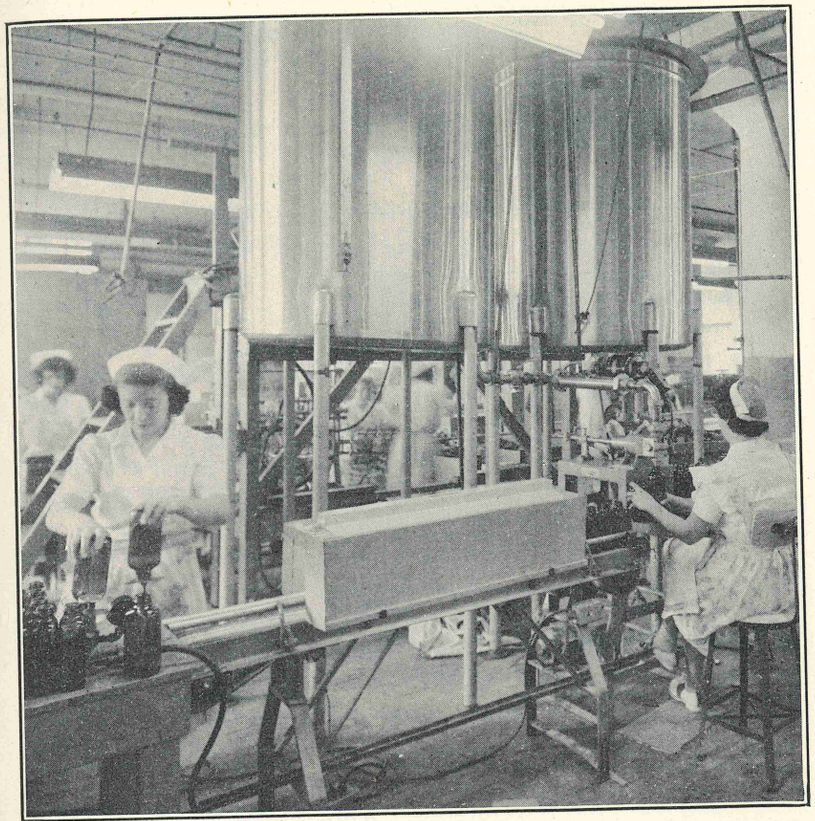


FIG. 7. Bottles on conveyer pass through tunnel under high intensity ultraviolet radiation before filling. (Courtesy of General Electric Co.)

wrappers, bottle caps, and the like are sterilized by suitably arranged lamps placed over conveyers, etc. The installation must be so engineered that the surface to be sterilized receives a sufficient intensity for a sufficiently long time to kill the organism. Figure 7 shows an installation in a pharmaceutical laboratory. Ultraviolet has also been used in the sterilization of drinking glasses, plates, and cutlery and for the sanitation of walls, fixtures, and the like in hotel bathrooms. All such applications depend for their success on having the surfaces initially clean

and free from dirt or films which would absorb the radiation and so afford the bacteria protection.

The killing of organisms in air has a twofold application. One is to the air in spaces where food and drugs are packed in order to prevent contamination of the product by bacteria or molds. The other is the sterilization of the air of occupied spaces to prevent the spread of airborne diseases.

Disinfection of Air

The design of any system for air sterilization depends upon the end in view, the sources of the contamination, the type of space, and the kind of occupancy of the space. The requirements for theatres, restaurants, and stores are quite different from those for schools and barracks, and those in turn are quite different from those for hospital wards and operating rooms.

Air being brought into a room or building can readily be sterilized by properly placed lamps in the ventilating duct. The size and shape of the duct, the ultraviolet reflection of the walls, and the number and arrangement of the lamps determine the efficiency. The essential features of these arrangements is to insure that all the bacteria passing through the duct are subjected to sufficient irradiation.

If the air velocity is too high the organisms do not receive a sufficient dose for killing. This is shown in the data of Table 3 which is for a duct 24 in. in diameter with nonreflecting walls and a 30-watt germicidal

TABLE 3 *

Cu ft/min	Survival Ratio
78	0.0015
153	0.015
306	0.077
614	0.216

* From M. Luckiesh, *Gen. Elec. Rev.*, **45**, 223 (1942).

lamp located along the axis of the duct. Increasing the air velocity from 78 cu ft per min to 153 cu ft per min, a factor of 2, increases the survival ratio tenfold. For higher survival ratios the effect is less marked.

If the inside of this duct is painted with an aluminum paint having a coefficient of reflection of 65 per cent, so that the radiation is reflected instead of being absorbed and so lost, the air velocities for a given survival ratio can be approximately doubled.

The engineering features of ducts have been worked out in great

detail by Luckiesh and Holladay, from whose paper Table 4 is taken. This table shows the calculated effects of various lamp arrangements in ducts of various shapes and sizes.

For 1/100 per cent survival in ducts with reflecting walls the cubic feet of air disinfected *per lamp* per minute varies from 255 for a duct 2×4 ft in diameter to 2350 for a duct 16×16 ft in diameter.

A duct system, however, can only guard against contamination in the incoming air and is powerless against contamination introduced by the occupants.

Disinfection of Air in Occupied Rooms

In an occupied room the occupants may be considered as introducing a constant number of bacteria into the air of the room per unit time by coughing, sneezing, stirring up dust, and the like. At the same time the ventilation of the space removes a certain number with each unit volume of air removed. Thus ventilation may be thought of as diluting the contaminated air with fresh air and thus reducing the bacteria count. The equilibrium concentration is the resultant of these two factors. In the average house the ventilation as the result of infiltration is of the order of 6 displacements of the air in the house per hr. In a tightly sealed house it is less, of course, and with windows and doors open it will be considerably greater.

An effect equivalent to ventilation in so far as the bacterial population is concerned may be obtained by suitably placed germicidal lamps. These are placed so as to irradiate the air in the upper one-third of the room and thus effectively sterilize this upper air. This germ-free air mixes with the contaminated air in the lower part of the room by convection, thus diluting the bacterial population as effectively as by ventilation with fresh outside air. Similarly, convection continually carries contaminated air to the upper part of the room. By means of a small number of properly placed lamps in a room it is easy to get as much lowering of the bacteria count in the room as would be obtained by ventilating the room at the rate of 100 displacements per hour. This is far in excess of any effect which can be obtained by ventilation. It is not possible to obtain more than 25 to 30 changes per hour without objectionable drafts.

The design of reflectors and the placing of lamps in installations for disinfecting air raises numerous engineering problems. In addition to performing their desired function, the fixtures must be arranged so that the amount of direct and scattered radiation is kept below the level that will produce conjunctivitis, erythema, or other possible harmful effects.

TABLE 4

COMPUTED VALUES OF THE NUMBER OF CUBIC FEET OF AIR THAT MAY BE DISINFECTED PER MINUTE PER 30-WATT 36-IN. GENERAL ELECTRIC GERMICIDAL LAMP WHEN LAMPS ARE ARRANGED IN VARIOUS WAYS IN VARIOUS DUCTS FOR VARIOUS PROPORTIONS OF *B. coli* SURVIVING IRRADIATION *

Duct			Lamps		Cubic Feet of Air Disinfected per Minute per Lamp for Various Survival Ratios			
Cross Section (Feet)	Length (Feet)	Reflection Factor (Per Cent)	Number	Arrangement	10%	1%	1/10%	1/100%
2 ft diam.	5	0	1	Series	725	340	215	156
4 ft diam.	10	0	2	Series	1430	685	420	305
8 ft diam.	20	0	4	Series	2900	1360	850	615
2 × 2	5	0	1	Series	805	375	225	165
3 × 3	9	0	2	Series	1220	550	345	248
4 × 4	10	0	2	Series	1570	725	470	330
8 × 8	20	0	4	Series	3020	1465	915	660
16 × 16	40	0	8	Series	6200	2910	1835	1300
2 × 3	5	0	1	Axial	920	425	260	185
2 × 4	6	0	1	Axial	1015	455	275	200
2 × 5	6	0	1	Axial	1090	465	285	205
4 × 4	10	0	8	Multiple-series	1750	832	535	390
16 × 16	40	0	32	Multiple-series	6850	3250	2075	1525
2 × 4	9	0	2	Multiple	1195	550	345	255
3 ft diam.	9	0	2	Crossed and transverse	1680	785	515	355
3 × 3	12	0	2	Crossed and transverse	....	790	....	....
3 × 3	9	0	2	Crossed and transverse	1630	735	455	320
3 × 3	7	0	2	Crossed and transverse	....	685	....	....
3 × 3	5	0	2	Crossed and transverse	....	600	....	....
3 × 3	3	0	2	Crossed and transverse	....	460	....	....
2 × 3	8	0	1	Transverse	1290	600	385	270
2 × 3	12	0	1	Transverse	1640	740	495	350
2 ft diam.	5	65	1	Series	1120	525	350	255
4 ft diam.	10	65	2	Series	2215	1055	695	500
8 ft diam.	20	65	4	Series	4450	2120	1340	1000
2 × 2	5	65	1	Series	1185	545	350	255
4 × 4	10	65	2	Series	2410	1140	745	550
8 × 8	20	65	4	Series	4830	2300	1520	1100
16 × 16	40	65	8	Series	9800	4550	2970	2150
2 × 3	5	65	1	Axial	1420	660	425	305
2 × 4	6	65	1	Axial	1570	730	455	340
2 × 5	6	65	1	Axial	1700	770	490	350
4 × 4	10	65	8	Multiple-series	2500	1200	795	590
16 × 16	40	65	32	Multiple-series	10200	4920	3270	2350
8 × 8	20	0	4	Series	....	1465	....	....
8 × 8	20	20	4	Series	....	1570	....	....
8 × 8	20	40	4	Series	....	1800	....	....
8 × 8	20	60	4	Series	....	2190	....	....
8 × 8	20	80	4	Series	....	2870	....	....

* These lamps had an output of 10,050 mw of energy of λ2537 A.

The Council of Physical Therapy of the American Medical Association [19] specifies that the total intensity of ultraviolet diffusely reflected and directly incident on the occupant for 7 hr or less should not exceed 0.5 μw per cm² and for continuous exposure should not exceed 0.1 μw per cm².

Figures 8*a* and 8*b* show schematically two fixture arrangements for irradiating the upper air of a room. In placing the lamps, advantage is taken of the convection currents wherever possible, so that the organisms will spend the maximum time in the ultraviolet beam. The path of the ultraviolet is made as long as is consistent with other factors, as any radiation which is absorbed by the walls rather than in the space is wasted so far as its usefulness in killing bacteria is concerned.

The distribution from a typical fixture is shown in Fig. 9. As much as possible of the energy is thrown into a nearly horizontal beam. No radiation is allowed to escape from the fixture in a downward direction in order to protect the occupants of the room from erythema and conjunctivitis. Relatively little is reflected upwards at a sharp angle for two reasons: first, the short path to the ceiling would be an inefficient use of the radiation; and, second, the reflection from the ceiling would be undesirable.

The number of lamps required to give 99 per cent disinfection of the upper air in a number of rooms of different sizes is shown in Table 5. Approximately half the number of lamps shown in this table is required if only 90 per cent disinfection is required. The efficiency of the installations increases materially with the height of the ceiling. Although such an installation is extremely effective in reducing the bacteria count in enclosed spaces, it must be emphasized that it does so by virtue of the fact that organisms are carried about the room in the path of the radiation for a considerable length of time by convection currents. No ultraviolet system can cope with contagion due to direct contact or to the passage of projected droplets from one person to another as in sneezing, coughing, and speech. However, it is effective in sterilizing the droplet nuclei, the small residues which result from the evaporation of droplets and which may remain suspended in air for long periods of time.

A different type of installation has been used in hospitals. In this type of installation, instead of placing the lamps so as to disinfect the communal air supply, the ultraviolet is used as a barrier. The lamps are placed so that the air which passes from one patient to another must first pass through a curtain or barrier of ultraviolet radiation. The infants' hospitals which are based on the cubicle system are well adapted to this type of installation. Lamps are placed around the edge of each

TABLE 5

NUMBER OF GERMICIDAL LAMPS REQUIRED FOR STERILIZATION OF AIR IN ROOMS OF VARIOUS SIZES *

11- to 13-Foot Ceilings

Room Lengths in Ft		10–13		14–18		19–24		25–31		32–39		40–48		49–58	
Germicidal Lamp Sizes		15 w	30 w	15 w	30 w	15 w	30 w	15 w	30 w	15 w	30 w	15 w	30 w	15 w	30 w
Room Widths	% Upper Air Disinfection														
10–13	99	2	1	2	1	2	1	3	1	5	2	6	3	8	4
14–18	99	..	..	3	1	3	1	4	2	6	3	7	3	9	4
19–24	99	..	..	..	..	4	2	5	2	7	3	9	4	11	5
25–31	99	..	..	..	..	..	..	6	3	9	4	10	5	12	6
32–39	99	..	..	..	..	..	..	..	..	10	5	12	6	14	7

* *Gen. Elec. Lamp Bulletin* LD-14.

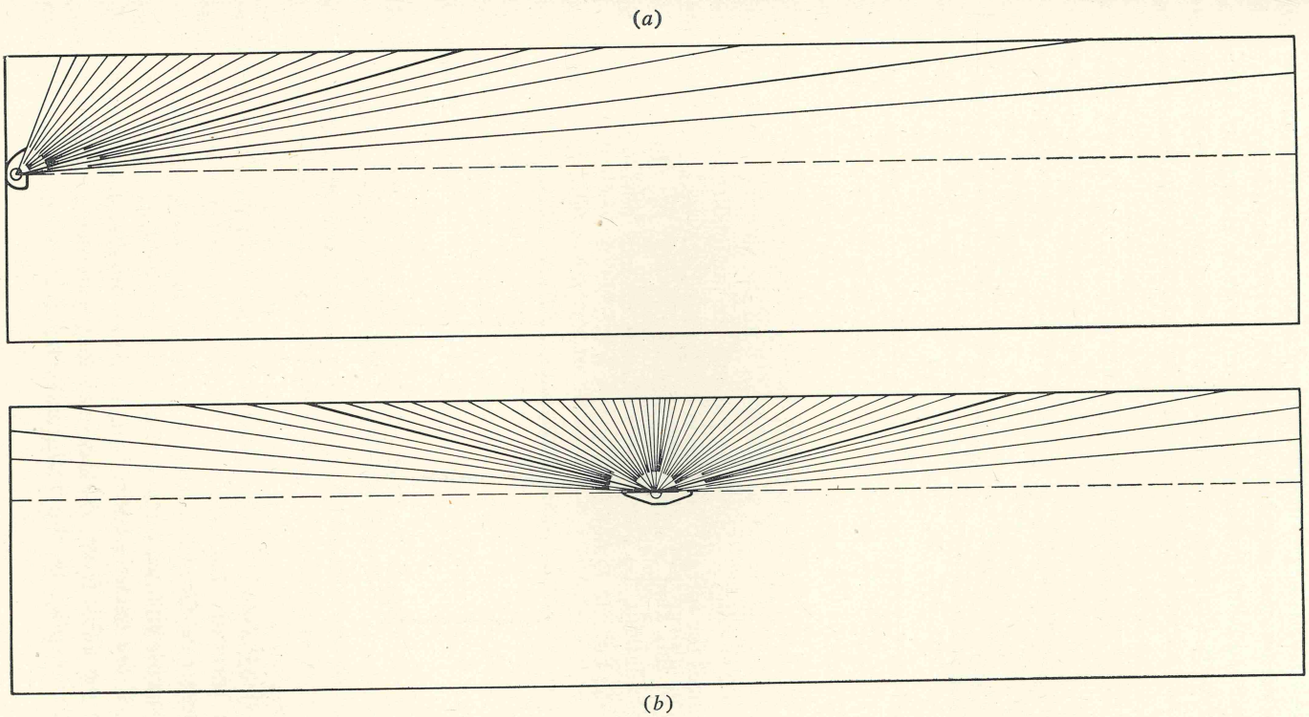


FIG. 8. Fixture arrangements for irradiating upper air of a room. *a.* Wall-type fixture. *b.* Centrally located fixture. (*Gen. Elec. Lamp Bulletin* LD-14.)

cubicle so that they throw an intense beam across the aperture but a negligible amount back into the cubicle or out into the room. The intensity of radiation in the curtain must be great enough so that the air is effectively sterilized in the time that it takes to pass through the relatively narrow barrier. This is not difficult to achieve in practice because

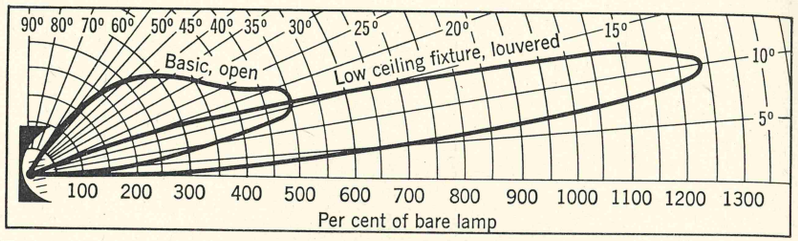


FIG. 9. Distribution of radiation from typical fixture. (*Gen. Elec. Lamp Bulletin* LD-14.)

of the small size of the aperture, usually comparable with an ordinary door. If each cubicle is so equipped, both the entering and the emerging air are sterilized. Since the patients are immobilized in the cubicles the chances for spread of infection are greatly decreased. An ultraviolet barrier of this kind is shown schematically in Fig. 10. In the most recent installations the curtain of radiation extends downward from the top of the cubicle rather than across it.

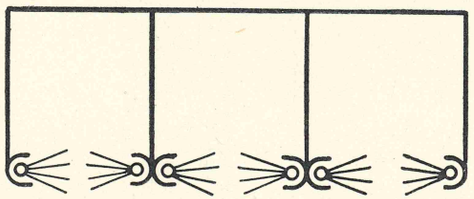


FIG. 10. Schematic diagram of an ultraviolet barrier across the entrance to hospital cubicles.

The effectiveness of such a barrier was tested in the Children's Hospital in Toronto. Bacteria were sprayed into the air in one cubicle at a constant rate throughout the experiment, and measurements of bacteria concentration were made in an adjoining cubicle. With the lamps turned off the bacteria count built up to an equilibrium value of 8000 colonies per cubic foot. At this value they were being removed by ventilation, adsorption on the walls, and other factors as fast as they were

being introduced. In the first minute after the lamps were turned on the count dropped to about 1000, and 8 min after turning on the lamps it was about 100. As soon as the lamps were turned off the bacteria concentration rapidly returned to its initial value. Bacteria of the air are closely associated with dust particles on floors. Consequently, any activity in a room which raises dust increases the bacteria count in the air. It has been found that floor irradiation in an experimental chamber produced a significant lowering in concentration of airborne bacteria.[20] Floor irradiation where it can be carried out is probably a valuable adjunct to ceiling irradiation.

The residual contamination of air which remains in hospital operating rooms after the most rigid aseptic precautions can be greatly reduced by irradiation.

Experiments which have been carried out in schools, children's hospitals, and military barracks have shown that the spread of colds and other respiratory infections can be significantly reduced by installations of this kind. In one installation in a naval training center there was a reduction of 25 per cent of respiratory illness in the barracks equipped with ultraviolet as compared with illness in adjacent control barracks.[21] In a number of experiments in children's hospitals there was a significant decrease in the number of cross infections where ultraviolet was used in comparison with controls. Ultraviolet disinfection is most effective under conditions where there is rigid control of the population of the space. The killing of germs by ultraviolet is well established. However, the effect of air disinfection on the spread of disease remains a matter for more complete investigation. The advisability and practicability of more general disinfection of air is a matter which will have to be decided by the medical profession when more information is available.

Disinfection of Water

Ultraviolet may be conveniently used to sterilize water as well as other clear liquids having a high transmission for short-wave ultraviolet. Its advantage for this purpose is that it does not introduce undesirable changes in taste as chemical methods do. Its present disadvantage is chiefly the economic one of high cost in comparison with chemical methods.

In order to be effectively sterilized the water must have a high transmission for ultraviolet and must be free from suspended matter which might shield bacteria from the radiation. Chapter 5 shows that most municipal water supplies fulfil the first requirement. The second can be met by filtering the water if necessary.

The design of systems depends upon the particular requirements. Immersion of the lamp directly in the water is unsatisfactory because of the formation of deposits on the arc tube and the decrease in ultraviolet output because of the cooling of the tube by the water. The lamp may be installed in a reflector over a tank as shown, for example, in Fig. 11.

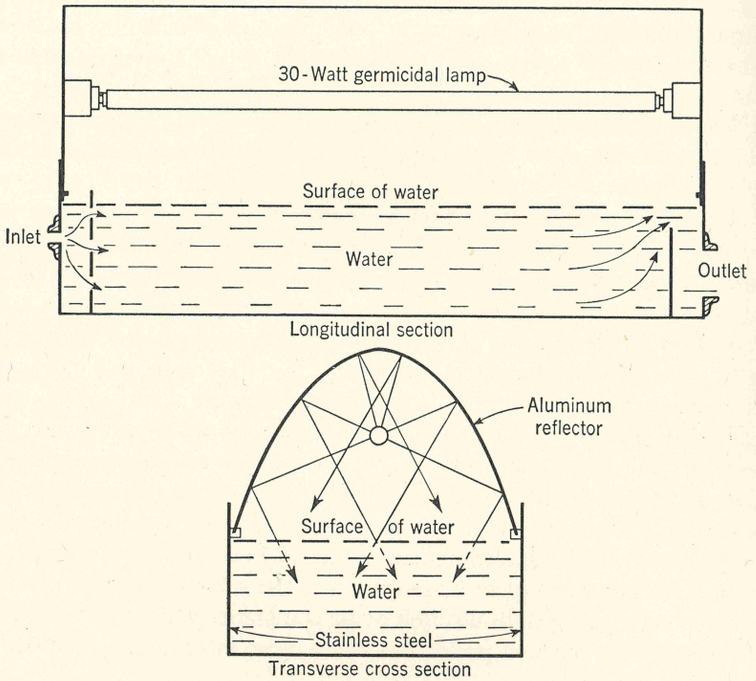


FIG. 11. Water sterilization installation. (M. Luckiesh, *Gen. Elec. Rev.*, **47**, 49, 1944.)

The tank should preferably be deep enough to absorb practically all the ultraviolet, as any radiation absorbed by the walls is wasted. The arrangement of inlet and outlet is such as to insure thorough mixing. When the lamp has to be installed in the water it may be installed inside a quartz tube. This avoids the cooling and consequent loss of lamp efficiency which would result if the water were in contact with the lamp wall. It also makes the cleaning and replacing of the lamp easier.

The amount of water which can be treated to give 0.01 survival ratio varies from 6000 gal per hr per 30-watt lamp to 600 gal per hr per

30-watt lamp for a variation in transmission coefficient from 0.03 per cm to 0.3 per cm.[22]

The degree of disinfection, i.e., the survival ratio, depends upon the intensity of the source, the transmission, depth and rate of flow of the water, or, in other words, on the details of the particular system used. Figure 12 shows the intensity of 2537 A radiation at various depths below the surface of a number of samples of water of different absorption coefficients. These values are calculated from the usual exponential relation $I/I_0 = e^{-at}$. The value taken for the initial intensity is $0.98 \times I_0$ rather than I_0, because 2 per cent of the incident radiation is reflected at the surface of the water. The incident intensity chosen in the figure is 100 μw per cm^2. Horizontal lines are drawn for 10 per cent survival ratio (90 per cent killing) and show the length of time required at the various intensities for 90 per cent killing. The intersections with the intensity versus depth lines give the maximum depth at which 90 per cent sterilization is obtained in the required time. If the initial intensity is greater than 100 μw per cm^2, the intensity at any given depth is increased in proportion and the exposure time for a given survival ratio is decreased in the same ratio.

Other Liquids

Ultraviolet may be used to sterilize other liquids besides water. Most organic liquids, however, have such low ultraviolet transmission that the depth of penetration is very small. In such liquids irradiation is possible only in very thin layers. One practicable method of irradiating such liquids is to allow the liquid to flow between concentric cylinders inside one of which the lamp is placed. Another is to allow the liquid to flow over an inclined plane which is irradiated by a lamp or bank of lamps.

In the treatment of milk it has been found that the use of short wavelengths results in undesirable flavors due to absorption of ozone and oxides of nitrogen as well as to a direct photochemical effect of the shorter wavelengths on the fats present in the milk. These effects are eliminated by filtering out the shorter wavelengths.

The use of ultraviolet radiation in the sterilization of blood plasma is at present under investigation.

Ozone

One of the noticeable features of ultraviolet lamps is the characteristic odor of ozone which is produced in their vicinity. Ozone, written O_3, is a modification of oxygen consisting of three atoms of oxygen. It is

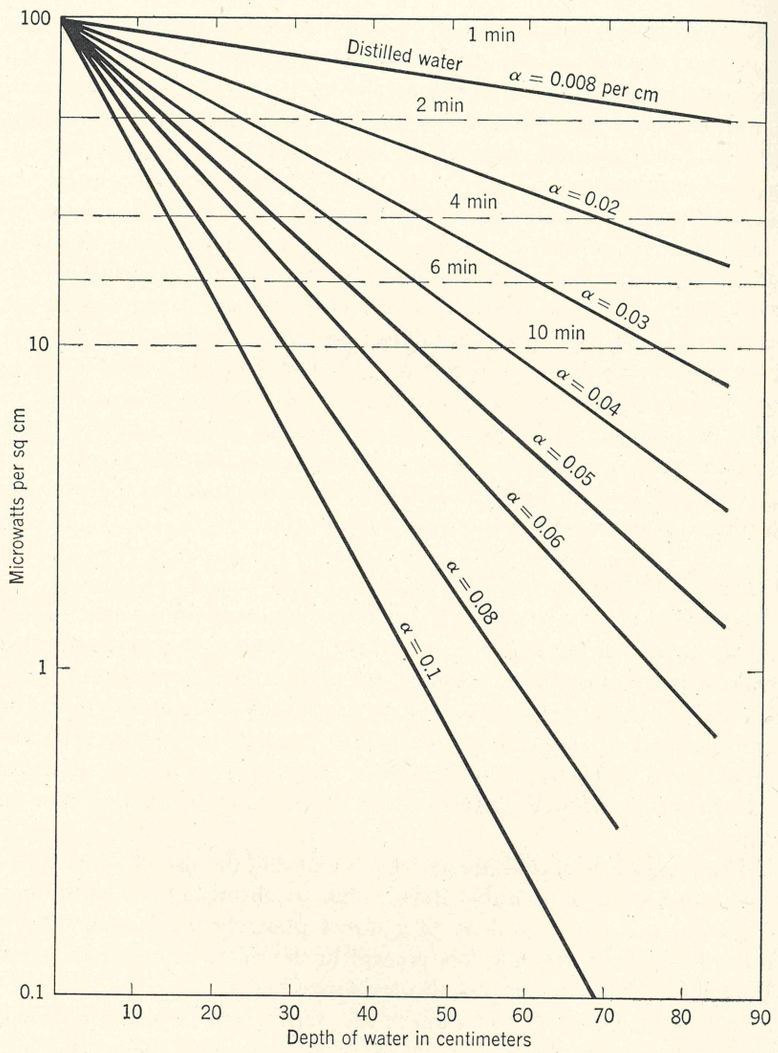


FIG. 12. Intensity of 2537 A radiation as a function of depth below the surface of water for the various values of absorption coefficient.

a colorless gas. It boils at −112°C. It is a very powerful oxidizing agent but in the absence of moisture and oxidizing agents is relatively stable. In a clean, dry glass vessel in the dark at room temperature it has a half life of about 15 hr; that is, half of the amount initially present decomposes to O_2 in 15 hr.

The nose is a very sensitive detector of ozone. A keen sense of smell can detect a concentration of 0.01 part per million (written as 0.01 ppm) by volume; as little as 0.1 ppm is objectionable to all normal persons and is irritating to the mucous membranes of the nose and throat in most persons. One to ten ppm cause headache, respiratory irritation, and possible coma.

According to Thorp [23] the toxicity of pure ozone is very much less than that of ozone containing oxides of nitrogen. He concludes that concentrations of pure ozone as high as 2.5 ppm by volume may be tolerated for long periods. According to his interpretation, the earlier studies of the toxicity of ozone were made with ozone containing high concentrations of oxides of nitrogen. This is a subject requiring further investigation.

The quantity of ozone ordinarily present in the lower atmosphere is negligible. It is noticeable in the vicinity of a lightning stroke. The presence of a thin layer in the upper atmosphere has already been discussed in Chapter 4.

The details of the photochemical reaction by which ozone is produced are not well understood. It is known, however, that O_3 is produced from O_2 by ultraviolet radiation and that the efficiency of the reaction increases as the wavelength becomes shorter. Ozone is also decomposed by ultraviolet radiation.

Ozone is produced in the vicinity of any ultraviolet lamp which radiates a significant amount of energy at wavelengths shorter than 2537 A. In the case of quartz mercury arcs most of the ozone production is probably due to the 1849 A line. In rooms ventilated in the ordinary manner the concentration of ozone built up by quartz mercury arcs is not likely to exceed a few one-hundredths parts per million. The amount produced by sunlamps is usually not detectable.

A very convenient ozone generator can be made by enclosing a low-pressure quartz mercury arc in a glass container into which a stream of oxygen is introduced. A 15-watt low-pressure quartz mercury arc placed inside a glass cylinder, 6 in. in diameter and 24 in. long, filled with oxygen will build up an equilibrium concentration of ozone of 600 ppm. The final concentration is limited by the decomposition of the ozone by the ultraviolet. The rate of production decreases considerably

with increase in humidity. If oxygen is allowed to flow through the tube, the concentration of ozone in the outgoing gas stream will depend on the rate of flow as shown in Fig. 13. The concentration decreases with increasing rate of flow, although the yield in grams increases. The maximum efficiency of production as measured for a low-pressure quartz lamp is about 10 grams per kwhr. This could doubtless be increased by the use of a more efficient generator of short-wave ultraviolet, such

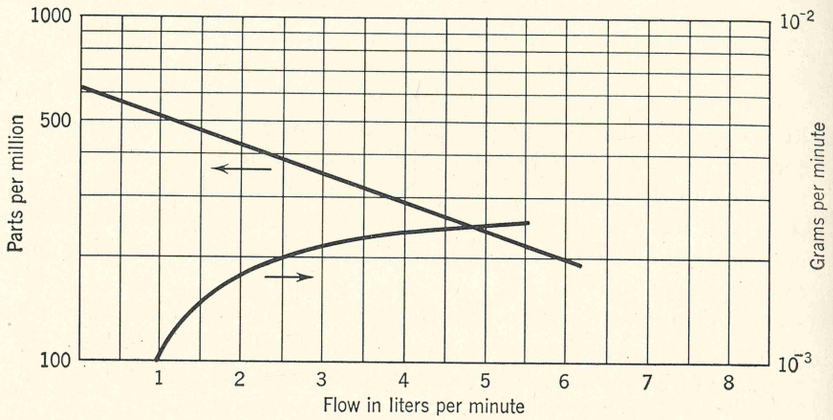


FIG. 13. Concentration of ozone produced from oxygen by low-pressure mercury quartz arc as a function of rate of flow of oxygen. (L. R. Koller, *J. Applied Phys.*, **16**, 816, 1945.)

as a lamp with very thin walls which would afford a higher transmission for 1849 A.

Ozone concentration can be measured by its absorption for 2537 A radiation. This can readily be done by passing the gas through a cell with quartz windows and using a photocell to measure the amount of energy from a germicidal lamp which passes through the cell. The ozone concentration can be calculated from the photocurrent by Beer's law

$$I/I_0 = e^{-act}$$

where I = the observed photocurrent.
I_0 = the photocurrent for 0 concentration of ozone.
a = the absorption coefficient for ozone, 276×10^{-6} cm^{-1}.
c = concentration of ozone in parts per million by volume.
t = length of absorption cell in centimeters.

With a 15-cm light path concentrations between 10 and 700 ppm by volume corresponding to values of I/I_0 of 0.96 to 0.056, respectively, can easily be measured.[24]

Low-pressure lamps in a glass which transmits a little of the shorter wavelength are used as ozone generators to reduce undesirable odors. The effect of odor removal may be partly due to an oxidation of the odorous vapors, or it may be due to a masking action of the ozone. This is a desensitizing action on the nose.

Fluorescent Lamps

Of all the applications of ultraviolet radiation the one which is immeasurably of the greatest practical and commercial importance is the fluorescent lamp. Because the ultraviolet is an intermediate step in the process of producing visible light rather than an end product, its importance is not generally recognized. The fluorescent lamp is essentially a highly efficient wavelength conversion device which transforms ultraviolet energy into light. It does this through the agency of a fluorescent substance called a phosphor.

A phosphor (from the Greek, light bearer) is one of a class of materials which have the property of absorbing energy and releasing it again in the form of luminescence. Luminescence differs from incandescence in that the radiation is not due to the temperature of the source. The luminescence may be either fluorescence or phosphorescence. Fluorescence refers to radiation excited while the phosphor is being irradiated, and phosphorescence refers to the radiation which is emitted after the exciting radiation has ceased.

In the fluorescent lamp the phosphor is applied as a coating on the inside wall of the lamp bulb. A discharge through a low pressure of mercury vapor takes place within the lamp. This is an efficient ultraviolet generator, as has been discussed in Chapter 2. In this case, however, the ultraviolet does not escape from the lamp through the ordinary glass which is opaque to ultraviolet. Instead it is absorbed by the phosphor coating which fluoresces and reradiates the adsorbed energy as longer-wavelength visible energy. Figure 14 shows in schematic form the construction and circuit of a fluorescent lamp.

There are a large number of luminescent materials, both organic and inorganic, solid, liquid, and gaseous. Some are found in nature, and many are synthetic products. Those used in fluorescent lamps are inorganic crystalline solids; mostly silicates, sulfides, tungstates, borates, and phosphates. The pure materials for the most part do not fluoresce or do so only very feebly. They owe their activity to a small amount

of a metallic impurity present in quantities as small as 0.01 per cent. This impurity is called an activator. The properties of the phosphor depend upon the nature and amount of the activator and upon the treatment in processing the phosphor.

The spectrum of solid luminescent materials extends in broad bands over limited regions. The nature of the spectrum, that is, the relative intensity at different wavelengths, is practically independent of the wavelength of the exciting radiation. No excitation takes place unless the

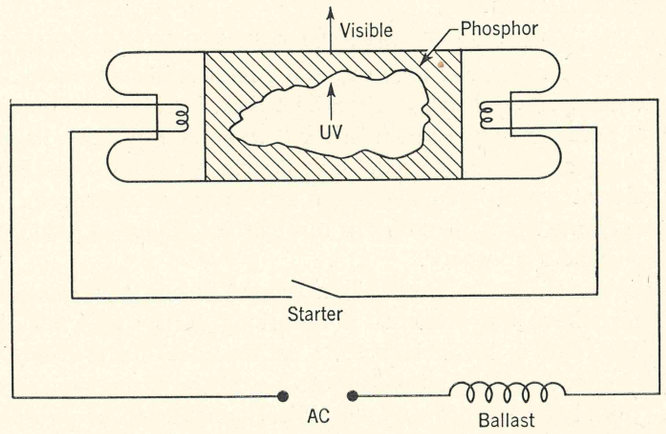


FIG. 14. Construction and circuit for fluorescent lamp.

exciting radiation is strongly absorbed, but within the limits of the absorption band the spectrum of the emitted radiation is independent of the exciting wavelength. In fact, the emitted radiation usually is of the same character for such different kinds of excitation as ultraviolet, X-rays, and cathode rays. The intensity of the luminescence increases with the intensity of the exciting radiation.

The characteristics of some of the phosphors commonly used in lamps are summarized in Table 6.

The fluorescent lamp has a high efficiency for the production of visible radiation. This is partly because the discharge process is an efficient one for converting electrical energy into ultraviolet (Chapter 2) and also because the fluorescence process for conversion of ultraviolet into visible is an efficient one. For the best phosphors the quantum efficiency of this process is nearly unity. That is, for each quantum of ultraviolet absorbed one quantum of visible radiation is emitted. This does not mean that the energy efficiency of this process is 100 per cent.

TABLE 6

CHARACTERISTICS OF PHOSPHORS USED IN FLUORESCENT LAMPS *

Phosphor	Lamp Color	Exciting Range † in Angstroms	Sensitivity Peak in Angstroms	Emitted Range in Angstroms	Emitted Peak in Angstroms
Calcium tungstate	Blue	2200–3000	2720	3100–7000	4400
Magnesium tungstate	Blue-white	2200–3200	2850	3600–7200	4800
Zinc silicate	Green	2200–2960	2537	4600–6400	5250
Zinc beryllium silicate	Yellow-white	2200–3000	2537	4800–7500	5950
Cadmium silicate	Yellow-pink	2200–3200	2400	4800–7400	5950
Cadmium borate	Pink	2200–3600	2500	5200–7500	6150
360 BL phosphor	Blue-ultra	2200–3200	2500–2800	3200–4500	3600
E phosphor	Blue-ultra	2200–2650	2475	2700–4000	3250
Halophosphate	White	1800–3200	2500	3500–7500	5800

(Mixtures of magnesium tungstate and zinc beryllium silicate in various proportions give various shades of white.)

* From W. E. Forsythe and E. Q. Adams, *Fluorescent and Other Gaseous Discharge Lamps*, Murray Hill Books, New York, 1948, p. 108.
† 2200 A lower limit of measurements.

For example, if the exciting radiation is of wavelength 2537 A, the energy per quantum is $h\nu = hc/\lambda = 7.8 \times 10^{-12}$ erg. If the radiation emitted is, let us say, at wavelength 5074 A, the energy per quantum is $h\nu = hc/\lambda = 3.9 \times 10^{-12}$ erg. Thus the energy efficiency would be 50 per cent. The efficiency of the conversion of ultraviolet to visible radiation is greater the less difference there is in wavelength between the emitted and the exciting radiation.

Optimum Thickness. The size of the individual grains and the thickness of the coating are an important factor in the performance of fluorescent lamps. Since the visible radiation is produced by the absorption of the ultraviolet in the phosphor layer, the latter must be sufficiently thick to absorb all the ultraviolet if high efficiency is desired. If the layer is too thin, the ultraviolet passes through it without being absorbed and so is wasted. On the other hand, if the coating is excessively thick, although the ultraviolet may be completely absorbed, the visible radiation must come out through such a thick layer of phosphor that an appreciable fraction of it is absorbed too. Accordingly, there is an optimum thickness for the phosphor layer. This is of the order of about 10 μ. A coating of this thickness will absorb about 99 per cent of the 2537 A radiation and will absorb 7 to 10 per cent of the light excited by this radiation.[25] The optimum thickness varies with factors such as the nature of the phosphor, the grain size, and the method of application.

Efficiency. The energy transformations in a 40-watt fluorescent lamp are shown in Fig. 15.[26] About 20 per cent of the total energy input to the lamp is converted into useful radiation in the visible part of the spectrum.

Flicker. Practically no energy is stored in an electric discharge lamp. Hence, on each cycle as the current passes through zero the light output falls almost to zero, resulting in a pronounced flicker. In the fluorescent lamp the phosphorescence of the coating which prolongs the glow after the exciting radiation has fallen to zero tends to reduce the flicker. This effect varies with the nature of the phosphor. It may be as much as plus or minus 95 per cent deviation from the mean candlepower for blue fluorescent lamps and as little as 10 per cent for the red. In practice the effect is minimized by operating two lamps out of phase in the same fixture.

Ultraviolet from Ordinary Fluorescent Lamps. The amount of ultraviolet from ordinary fluorescent lamps is negligibly small compared with that from sunlight. This is shown in Table 7. The ultraviolet from

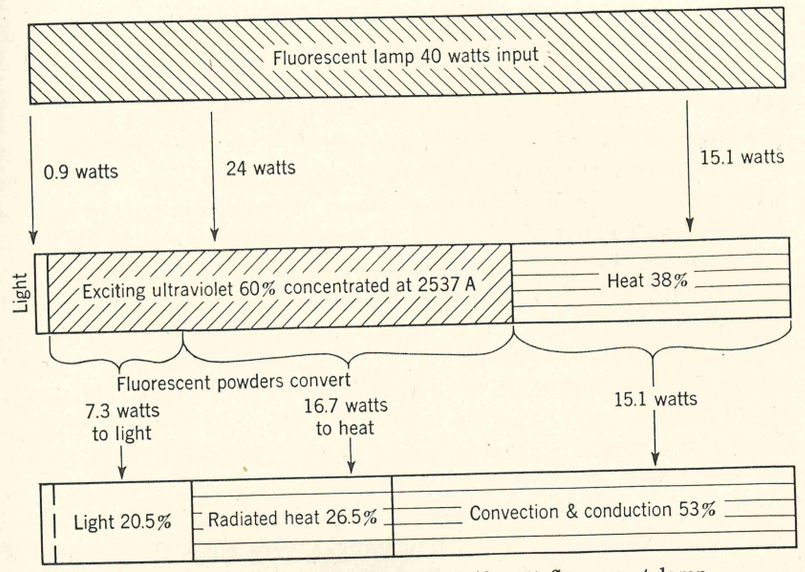


FIG. 15. Energy transformation in a 40-watt fluorescent lamp.

TABLE 7 *

ULTRAVIOLET FROM FLUORESCENT LAMPS

	Ft-Candles	Intensity of Ultraviolet Shorter than 3150 A, $\mu w/cm^2$ Absolute	Relative
Direct sunlight	6600	56	70
Skylight-clear blue sky	1900	117	146
Sunlight and skylight	8500	173	216
Direct fluorescent light 3500° white	50	0.8	1
		Intensity of Ultraviolet Less than 3150 A Erythemally Weighted	
Direct sunlight	6600	7.5	214
Skylight-clear blue sky	1900	15.6	450
Sunlight and skylight	8500	23.1	660
Direct fluorescent light 3500° white	50	0.035	1

* M. Luckiesh and A. H. Taylor, *Illum. Eng.*, **40**, 77 (1945).

daylight (6500°) fluorescent lamp is about 2.3 times that from white fluorescent lamps.

Fluorescent Black-Light and Sun-Tan Lamps

Many phosphors fluoresce to some extent in the ultraviolet, but only a small number are sufficiently efficient to be of any practical importance as sources of ultraviolet. Because of Stokes' law, namely, that the fluorescent radiation is always of longer wavelength than the exciting radiation, phosphors which emit ultraviolet radiation must be excited by ultraviolet of still shorter wavelength. Two types of commercial lamps have been developed in which ultraviolet radiation of wavelength 2537 A excites phosphors to emit ultraviolet radiation of somewhat longer wavelength. One of them is a phosphor which emits in the region around 3000 A and is used for therapy. The other emits at wavelengths around 3600 A, so-called black light, and is used to produce fluorescent effects in other substances.

The first type of lamp is a fluorescent sunlamp. It is a low-pressure mercury vapor lamp which is inherently a very efficient generator of 2537 A radiation. The bulb wall of this lamp is coated with a thallium-activated calcium phosphate phosphor. This material fluoresces entirely in the ultraviolet over a range of wavelengths from about 2600 to 4000 A with a peak at 3200 A. The bulb is made of a soda lime glass (No. 9821 having a transmission of 60 per cent at 2967 A for a thickness of 35 to 40 mils). This limits the radiation to the region above 2800 A. As is shown in Fig. 16 a substantial part of the radiation from this lamp is in the erythemally effective region 2800 to 3200 A. For this reason it is called an E phosphor.

A number of other phosphors which fluoresce in this same general region are listed in Table 8. Brightness and wavelength of excitation

TABLE 8 *

Phosphor	Peak Emission Wavelength in Angstroms	Relative Total Ultraviolet Energy, 2800–4000 Arbitrary Units
$Ca_3(PO_4)_2$:KCl(Tl)	3050	3.9
$CaKPO_4$(Tl)	3150	6.9
$Ca_3(PO_4)_2$(Tl)	3300	10.4
$BaFSiO_3$(Pb)	3500	18.0
$BaSiO_3$(Pb)	3200	7.2
$BaSi_2O_5$(Pb)	3500	15.5

* R. H. Clapp and R. J. Ginther, *J. Optical Soc. Am.*, **37**, 355 (1947).

and emission are not the only characteristics which must be considered in the choice of phosphors for lamps. Other considerations relate to manufacturing process and lamp life. When all these factors are taken into account, the $Ca_3(PO_4)_2$(Tl) appears to give the most satisfactory results in lamps. Fluorescent sunlamps can be made to have an efficiency of conversion of electrical into ultraviolet energy greater than that of ordinary gas discharge sunlamps.

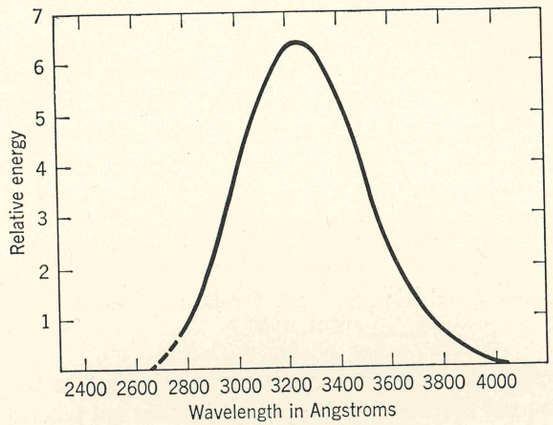


Fig. 16. Radiation from E lamps. (H. Froelich, *Trans. Electrochem. Soc.*, **91**, 241, 1947.)

The second type of lamp is also excited by 2537 A radiation and emits in the range 3500–4000 A. The phosphor used is a cerium-activated calcium phosphate. Its efficiency as a generator of this radiation is actually greater than that of high-pressure mercury vapor lamps. Its spectral emission curve is shown in Fig. 17. Since the emission peak is closer to 3600 A, it is designated as a 360 BL lamp meaning "Black Light" of wavelength predominately 360 μ. These lamps are very useful where diffuse sources of low brightness are required. They have been used for such applications as blueprinting, laundry-mark identification, and for dial illumination of airplane instrument panels. In this latter application the instrument dials and panel are painted with phosphors which are excited by long-wave ultraviolet. Thus the instruments can be read without any bright illumination to disturb the pilot's dark adaptation.

It is interesting to note that an attempt to produce an ultraviolet lamp having its output in a broad band from 3200 to 3700 A by mixing E

and 360 BL phosphors in the same lamp was not successful. The 360 BL phosphor is excited by the shorter wavelengths emitted by the E phosphor so that the two spectra are not simply additive. This spec-

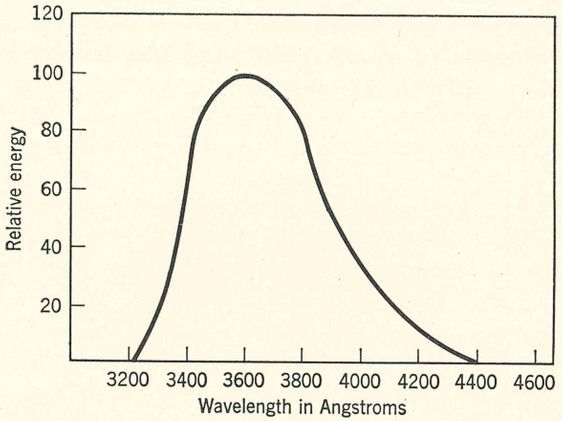


FIG. 17. Radiation from BL lamps. (H. Froelich, *Trans. Electrochem. Soc.*, **91**, 241, 1947.)

trum can only be achieved by combining the radiation from separate lamps so arranged that the 360 BL phosphor does not receive any radiation from the E phosphor.

FLUORESCENCE ANALYSIS

Another application of ultraviolet is the use of characteristic luminescence as a means of analysis. This method has been used for a wide variety of purposes, such as differentiation between seeds, bacteriology, study of plant tissues and diseases, drugs, foods, oils, fats, fuel oils, minerals and gems, paper, rubber, textiles, and dyestuffs. The material to be investigated is irradiated by ultraviolet, and the emitted fluorescent radiation is examined either visually or by a suitable detector. The fluorescent radiation is usually collected at right angles to the illuminating beam (in the case of liquid or transparent samples). Filters are used to prevent direct radiation from the source from reaching the detector. A fluorometer is indicated schematically in Fig. 18.

MERCURY VAPOR DETECTOR

Ultraviolet radiation is used in instruments for detecting the presence of mercury vapor. This substance is toxic when present in the atmosphere in concentrations greater than 1 mg per 10 cu m of air. Accordingly, in any industry using mercury it is important to be able to detect the presence of very minute quantities. This can be done readily because of the very strong absorption by mercury vapor of the resonance line of mercury, 2538 A.

A mercury vapor lamp which emits this radiation is used to excite a photoelectric tube. A sample of the gas to be tested is drawn through

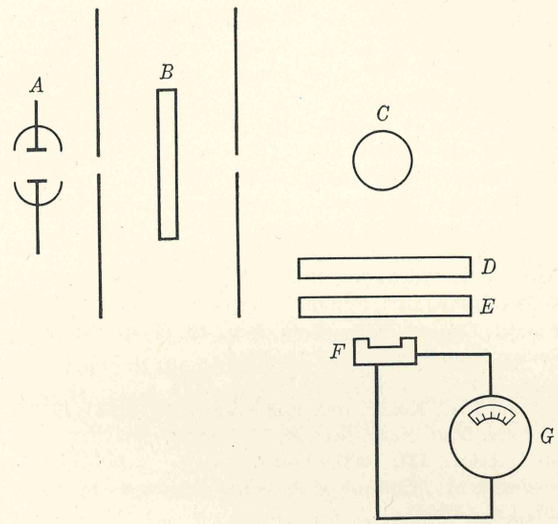


FIG. 18. Fluorometer. *A*. Ultraviolet source. *B*. Filter to exclude visible radiation. *C*. Sample. *D*, *E*. Filter to exclude ultraviolet. *F*. Photocell detector. *G*. Galvanometer.

a chamber separating the lamp and phototube. If mercury vapor is present, it absorbs some of the radiation; thus the amount of radiation reaching the phototube decreases, and so the photocurrent decreases. The commercial form of this instrument is able to detect concentrations of mercury vapor in air of from 0.03 to 3 mg per cubic meter, corresponding to from 0.004 to 0.37 ppm by volume, with an accuracy of approximately 5 per cent.

IONIZATION

A small amount of ionization is produced in the air surrounding a quartz mercury arc. The amount is insignificant for most practical purposes; however, it has been used to remove static charges from glassware. These charges cause trouble in making accurate analytical

weighings. An exposure of 5–10 min at 1–2 ft from a quartz mercury arc is sufficient to dissipate these charges.[27]

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8 Detectors of Ultraviolet Radiation

The measurement of ultraviolet radiation differs from that of visible radiation in that the eye cannot be used directly as a detecting instrument. Some other means of detection must be used. There are available three classes of detecting instruments—physical detectors, chemical detectors, and biological detectors. The physical detectors are the most important group. The chemical detectors, although used with considerable success in some of the pioneering work on ultraviolet, have largely been superseded by more convenient and more accurate photoelectrical devices. The biological detectors have little use except where better ones are not available.

Some of the more important properties of these three classes of detectors are listed in Table 1. With the exception of the thermopile, bolometer, and radiometer, which are known as radiometric devices, all ultraviolet-measuring devices are selective. That is, their sensitivity depends upon the wavelength of the radiation being measured and accordingly varies throughout the spectrum. These three are also the only detectors which may be used throughout the entire spectrum from the ultraviolet to the infrared. All the other detectors have a long-wave limit beyond which they cannot be used. The limit is usually in the ultraviolet or the near infrared, as is indicated in the third column of the table. The long-wave limit is not entirely a disadvantage. By choosing a detector with the proper long-wave limit the same effect is gained as if a filter which cut off all longer wavelengths were used.

The phototube detector is essentially independent of temperature. The other physical detectors are affected to some extent by ambient temperature. Where high accuracy is not required, however, the effects of temperature on the physical detectors may be neglected. All the chemical detectors are temperature sensitive.

TABLE 1

CHARACTERISTICS OF ULTRAVIOLET DETECTORS

Type of Detector	Selectivity	Range	Linearity	Sensitivity	Cumulative
Physical					
Radiometric	No	All wavelengths	Yes	High	No
Phototube	Yes	UV to near IR	Yes	High	No but can be in suitable circuit
Photovoltaic cell	Yes	UV to near IR	Yes	Intermediate	No
Photoconductive cell	Yes	UV to IR	No	Low	No
Fluorescence	Yes	UV to near IR	Yes	Low	No
Chemical					
Acetone (I.G. Farben, dosimeter, etc.)	Yes	UV	No	Low	Yes
Photographic plate	Yes	UV to near IR	No	High	Yes
Photographic paper	Yes	UV to near IR	No	High	Yes
Oxalic acid	Yes	UV to 410 mμ	Yes	Low	Yes
Zinc sulfide	Yes	UV to 350 mμ	No	Low	Yes
Biological					
Human skin					
Erythema	Yes	UV to 320 mμ	No	Low	Yes
Pigmentation (direct)	Yes	UV to 430 mμ	No	Low	Yes
Killing of bacteria	Yes	UV to 320 mμ	No	Low	Yes
Antirachitic effect	Yes	UV to 320 mμ	No	Low	Yes

The physical detectors, with the exception of the photoconductive cell, are linear. They give a response which is directly proportional to the intensity of the incident radiation. The chemical and biological detectors are cumulative devices; that is, they integrate all the radiation received over a considerable time interval. Phototubes in suitable circuits may also be used as integrating devices. The other physical detectors, however, cannot be used in this manner.

The problem of measuring ultraviolet would be a simple one if we had to deal only with monochromatic radiation. The difficulty lies in evaluating the complicated spectra of available sources.

RADIOMETRIC DEVICES

The nonselective radiation detectors depend for their response on the heating effect of the radiation. There are three main types: thermopiles, bolometers, and radiometers. The thermopile depends for its operation on the emf generated when the junction between two dissimilar metals is heated. The radiometer depends on the deflection of a very light vane suspended from a fine quartz fiber, when radiation is incident on it. The bolometer is a very delicate Wheatstone bridge, one arm of which is heated by the radiation to be measured. These instruments are most suitable as laboratory standards. They are very sensitive, but at the same time they are rather delicate. They are commonly used in spectroscopy but are not convenient for ordinary use.

PHOTOELECTRIC DEVICES

Three fundamentally different types of photoelectric devices are useful for measurement of radiation: phototubes, which depend upon the external photoelectric effect; photovoltaic cells, which depend upon a photoelectromotive force effect; resistance cells, which depend upon a photoconductive effect. Phototubes and photovoltaic cells are used extensively in measurements of ultraviolet. Resistance cells are unimportant for this application and are mentioned here only for the sake of completeness. Thallous sulfide and lead sulfide photoconductive cells are chiefly useful as detectors of red and infrared radiation.

PHOTOTUBES

The phototube is a two-electrode vacuum tube. Its operation is indicated schematically in Fig. 1. It consists of two electrodes in an evacuated container. For ultraviolet application this must be of quartz or ultraviolet-transmitting glass. In some tubes the negative electrode, or cathode, is a thin film of metal deposited on the tube wall. In others

it is a separate metal plate in the tube. A potential is applied between the two electrodes. When radiation falls upon the cathode, it emits electrons which are attracted to the anode. This flow of electrons or photocurrent is directly proportional to the intensity of the incident radiation. It is also practically instantaneous, the time delay being less than 10^{-9} second. In some tubes, a small amount of an inert gas, such as argon, is introduced into the bulb. This results in an amplification of the initial photocurrent by ionization by a factor of 5 to 10, and so

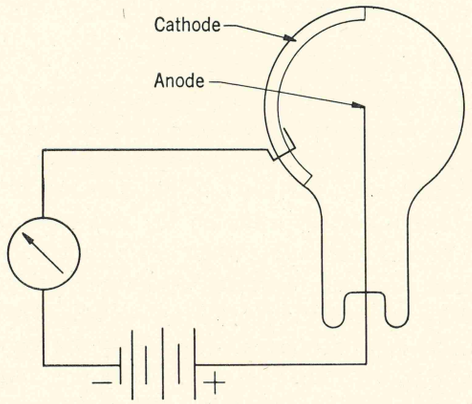


FIG. 1. Photoelectric tube and circuit.

the sensitivity is increased. This advantage is offset to some extent by a decrease in stability, a sensitivity to changes in applied voltage, a slight time lag, and poorer reproducibility.

The physical structure of phototubes varies somewhat with the application for which they are designed. Such physical features include the shape, size, spacing, and insulation of the electrodes and the shape, size, and material of the envelope. Several forms of phototubes are shown in Fig. 2. The most important single factor, however, is the nature of the cathode material, since it is this which determines the spectral response and sensitivity. This is discussed on page 244.

AMPLIFICATION OF PHOTOCURRENTS

The range of radiation intensity over which phototubes may be used is very great. At very high intensities the photocurrents may be limited to reasonable values by diaphragms or neutral filters. Very small photocurrents, which are too small to read on sensitive galanometers, corresponding to very low intensities of radiation may be measured by

using thermionic amplifiers to amplify currents sufficiently to read or record them on ordinary meters. Figure 3 shows an elementary photo-

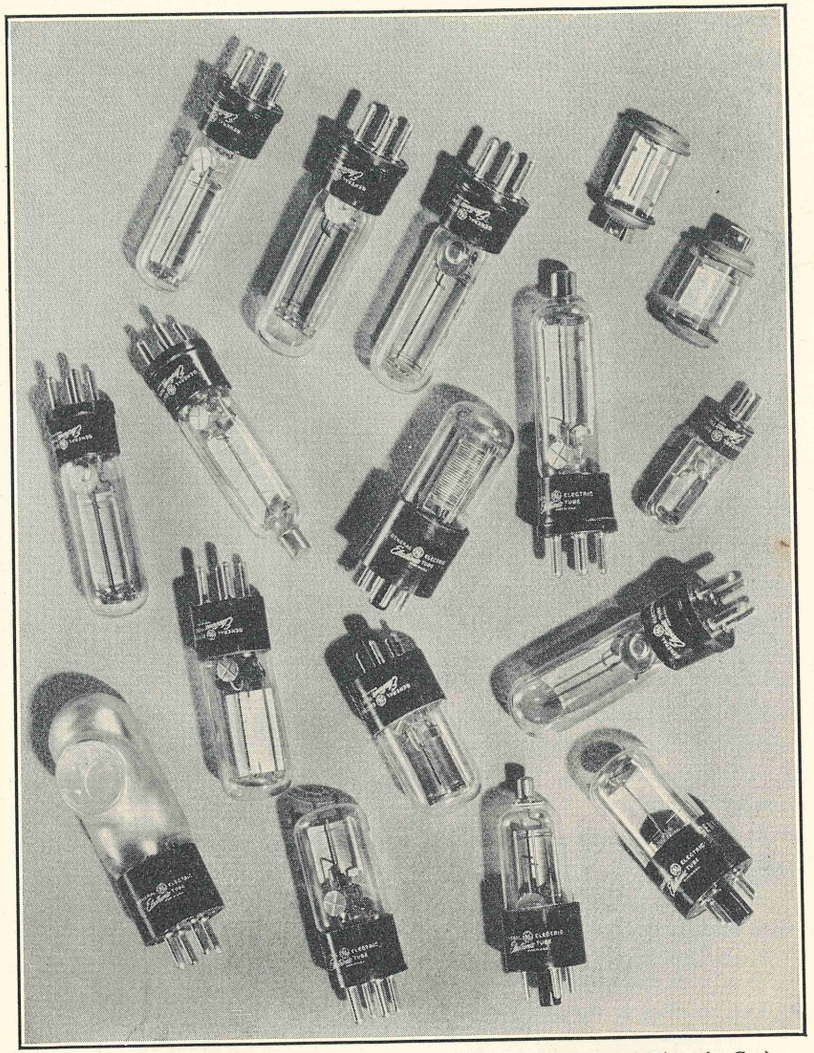


FIG. 2. Various types of phototubes. (Courtesy of General Electric Co.)

tube amplifier circuit. Numerous circuits of varying degrees of complexity for various applications have been developed for amplifying phototube currents. Photocurrents as small as 10^{-16} ampere can be

measured without undue difficulty. These correspond to radiation intensities of a few thousand quanta per second. Individual quanta may be detected with tubes of the Geiger-counter type.

An unusual kind of amplifier is used in the photomultiplier tube. In this tube secondary emission is employed as a means of amplifying the photocurrent within the phototube envelope. In addition to the usual photocathode and anode, this type of tube contains a number of other intermediate electrodes (usually nine) called dynodes. The photoelectrons from the cathode are caused to impinge on the first of these dynodes. Each photoelectron causes the emission of several secondary electrons. These secondary electrons are then caused to strike the next dynode, where each secondary again causes the emission of several additional secondaries. In this way the original photocurrent is easily amplified within the tube as much as 100,000-fold. This device is simple in operation as well as rugged and compact. A photograph is shown in Fig. 4*a* and a schematic diagram of the electrodes in Fig. 4*b*. Its chief disadvantage lies in the fact that it requires about 1000 volts for its operation. This limits its usefulness to places where a high-voltage power supply is available. Such power supplies, however, are now made in conveniently portable sizes.

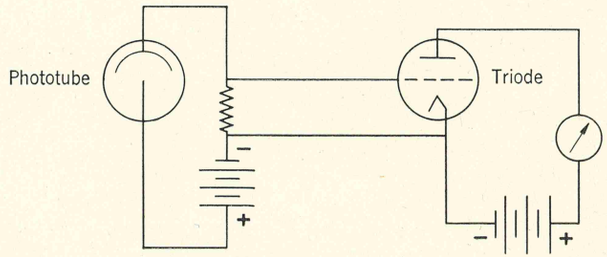


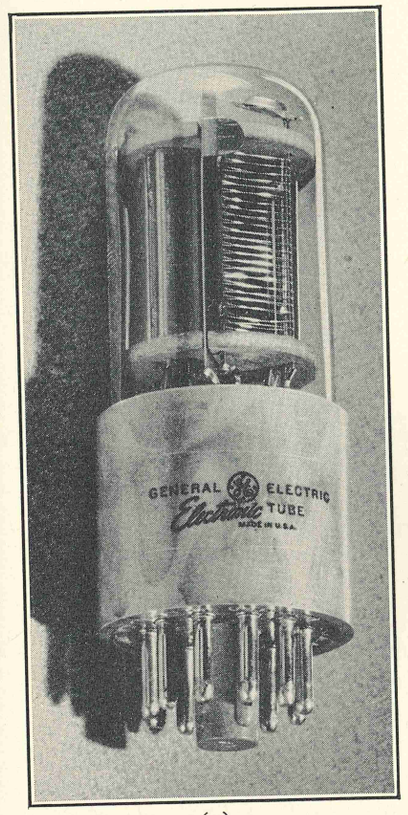
FIG. 3. Simple phototube amplifier circuit.

A present limitation is that photomultiplier tubes are available only with cesium cathodes. This is not a fundamental limitation but is one imposed by the technical aspects of the manufacturing process.

CLICK METER

A very ingenious circuit for use with phototubes was developed by Rentschler. This is a phototube circuit which does away with the necessity for a sensitive meter and provides a visible or audible signal instead as a measure of current. It can be used for very minute currents and also may be used as an integrating device.[1] The circuit shown in Fig. 5

consists primarily of a phototube in series with a source of emf and a condenser. The condenser charges up through the phototube at a rate determined by the impedance of the tube, the rate being proportional to the light intensity. Eventually, the condenser voltage reaches the breakdown voltage of the glow tube, and a discharge starts between A and C. This permits current to flow between the main anode B and A and to operate the counter or relay R. The condenser then discharges through the tube, and the voltage falls below the value necessary to maintain the discharge, and the current stops. The cycle is repeated at a rate determined by the intensity of the radiation. The visible flash through the tube may be used as an indication, or the click of a relay may be used



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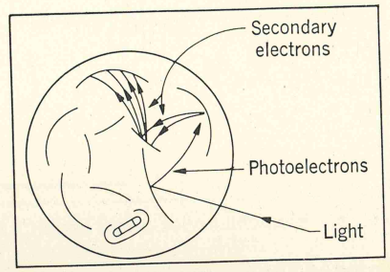


(*b*)

FIG. 4. Photomultiplier tube. *a*. Photograph. (Courtesy of General Electric Co.) *b*. Schematic diagram.

as an audible signal, or if desired the tube may be made to operate a counter. By proper choice of the size of the condenser the frequency of discharges for a given intensity of radiation may be adjusted to any convenient value. If the capacity is made large so that the time interval

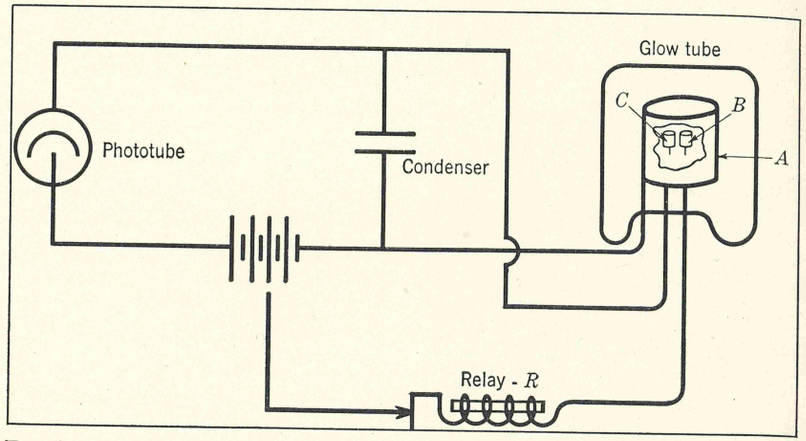


FIG. 5. Rentschler click-meter circuit. (*J. Am. Inst. Elec. Engrs.*, **49**, 113, 1930.)

between discharges becomes very large, the device integrates the ultraviolet received during the interval.

PHOTOTUBE SPECTRAL SENSITIVITY

The most important factor in determining the performance of a phototube is the nature of the cathode surface, since it is this which determines the spectral response and sensitivity. Since phototubes are selective devices, a knowledge of their spectral response characteristics is absolutely essential in order to be able to interpret their current indications. The metallic elements differ widely in this respect. In general, the spectral response curves are of the form shown schematically in Fig. 6. This curve shows the relative photocurrent for equal amounts of radiant energy throughout the spectrum. In general, the curve shows a decrease in photocurrent with increase in wavelength, falling to 0 at some wavelength called the long-wave limit. No radiation of longer wavelength than this produces any photocurrent so that a phototube is useful only for wavelengths shorter than its long-wave limit. The spectral response curve usually exhibits one or more maxima. On the short-wave side the response is usually limited by the transmission of the glass envelope.

Table 2 gives the long-wave limits for most of the metallic elements

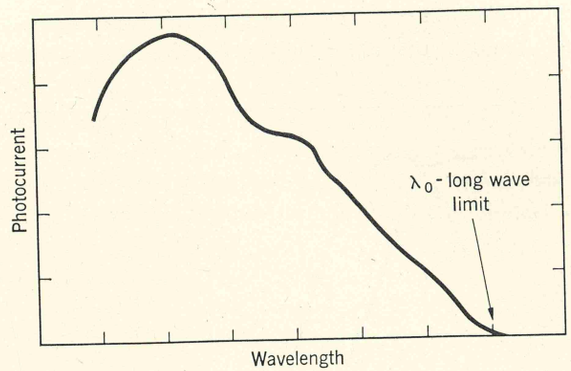


FIG. 6. Phototube spectral response curve.

TABLE 2

LONG-WAVE LIMITS FOR METALS

Element	Long-Wave Limit	Reference	Element	Long-Wave Limit	Reference
Lithium	5100	B *	Strontium	5500	B
Beryllium	3900	B	Zirconium	3300	Z
Sodium	5200	B	Columbium	3080	C ‡
Magnesium	3430	B	Molybdenum	2850	Z
Aluminum	2830	B	Rhodium	2500	B
Potassium	5500	B	Palladium	2488	B
Calcium	4000	Z †	Silver	2610	B
Titanium	3150	Z	Cadmium	2920	Z
Vanadium	3260	B	Tin	2740	B
Chromium	2840	Z	Tin B	2820	B
Manganese	3280	B	Cesium	6000	B
Iron	2680	B	Barium	5200	B
Cobalt	2720	B	Tantalum	3010	Z
Nickel	2550	B	Tungsten	2700	Z
Copper	2570	B	Platinum §	2000	Z
Zinc	2915	B	Gold	2560	B
Gallium	3000	B	Bismuth	2870	B
Germanium	2600	B	Cerium	4300	Z
Arsenic	2400	B	Thorium	3650	Z
Rubidium	5700	B	Uranium	3400	Z

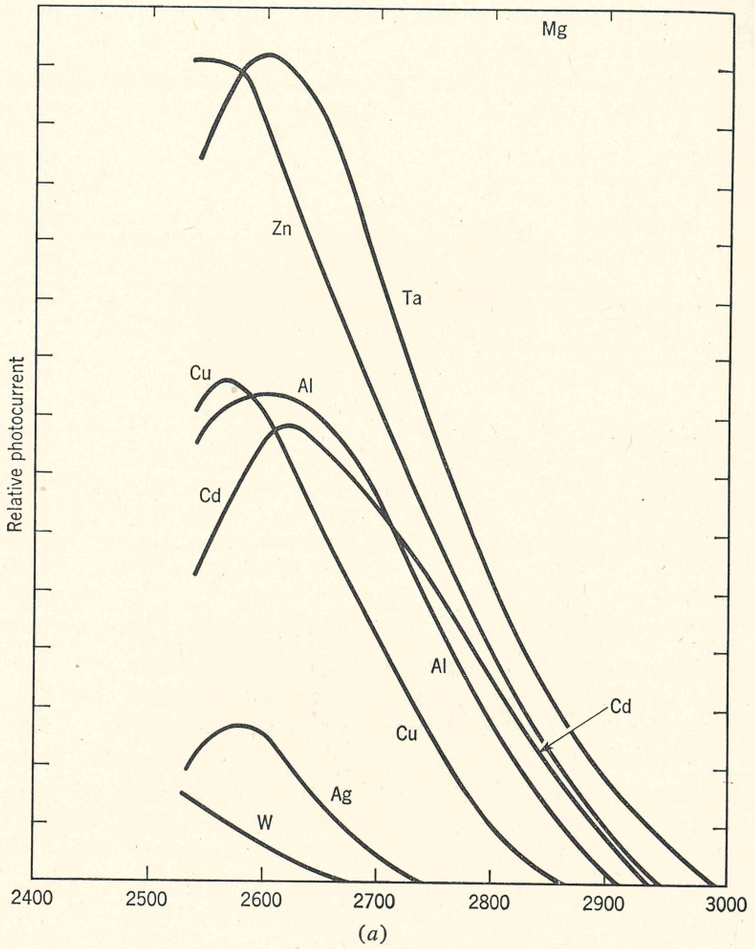
* B = *Tables Annuelles* 13, Hermann, Paris, 1937.

† Z = V. Zworykin and E. G. Ramberg, *Photoelectricity and Its Applications*, John Wiley and Sons, 1949.

‡ C = A. L. Reimann and C. K. Grant, *Phil. Mag.*, **22**, 34 (1936).

§ This value is probably due to contamination by oxygen. The value found by R. V. Whitney, *Phys. Rev.*, **50**, 1154 (1936), is 2320 A.

usually used in phototubes. It can be seen that most of the pure metals respond only to ultraviolet since their long-wave limits lie in this region.



(*a*)

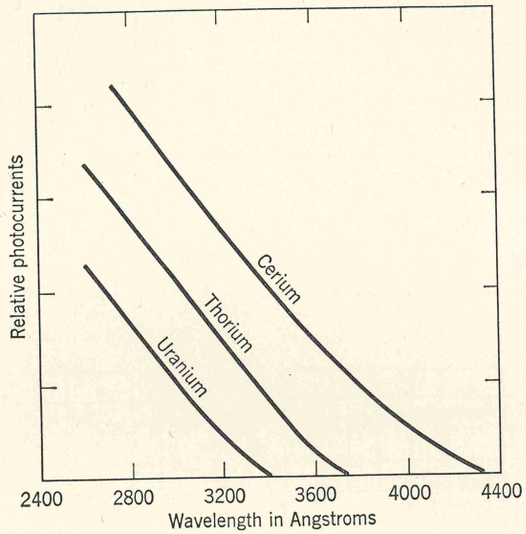
FIG. 7. *a* and *b*. Spectral response curves for various metals. (Atfer H. Rentschler, *J. Am. Inst. Elec. Engrs.*, **49**, 576, 1936.)

Only the alkaline earth metals and the alkali metals have long wave limits in the visible.

The values in Table 2 are for clean surfaces of the pure metals. It

is difficult to obtain such surfaces in practice, and the values are affected to a marked degree by very slight traces of impurities. The result is that phototubes made of these materials may have long-wave limits differing significantly from the values given in the table.

The alkali metals, rubidium and cesium, are not used in the pure form on account of their low melting point and high vapor pressure. In the combined forms which are used in phototubes their long-wave limits are



(*b*)

FIG. 7. (*Continued*).

farther in the visible or near infrared than the values given in Table 2.

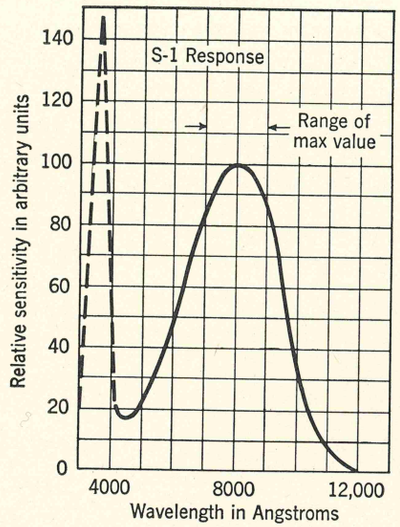
The various cathode materials have been grouped below according to the portion of the spectrum in which they are useful:

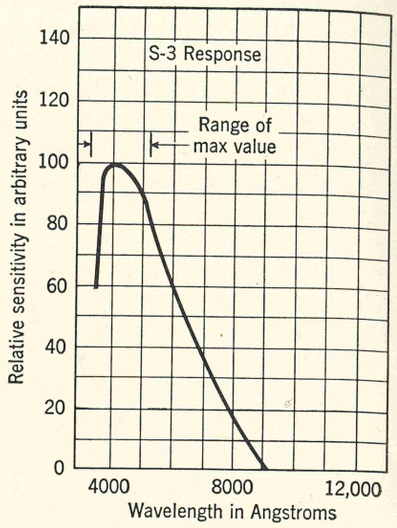
Phototubes sensitive only to radiation shorter than 2537 A
rhodium, palladium, platinum

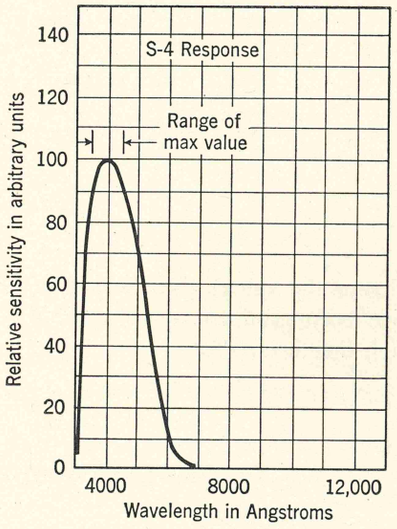
Phototubes sensitive only to radiation shorter than 3000 A
aluminum, chromium, iron, cobalt, nickel, copper, zinc, gallium, molybdenum, silver, cadmium, tin, tungsten, gold, bismuth

Phototubes sensitive only to radiation shorter than 3650 A
magnesium, titanium, vanadium, manganese, zirconium, tantalum, thorium, uranium

Phototubes sensitive to visible radiation
lithium, sodium, potassium, rubidium, cesium, calcium, barium, strontium







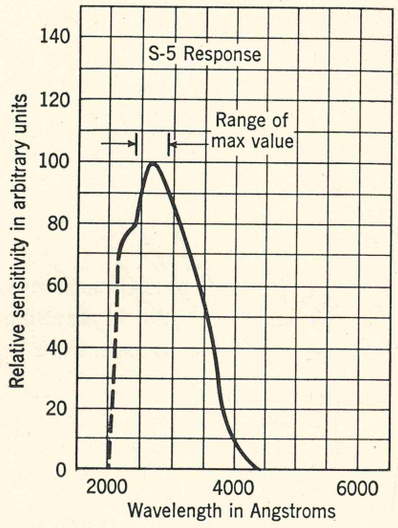
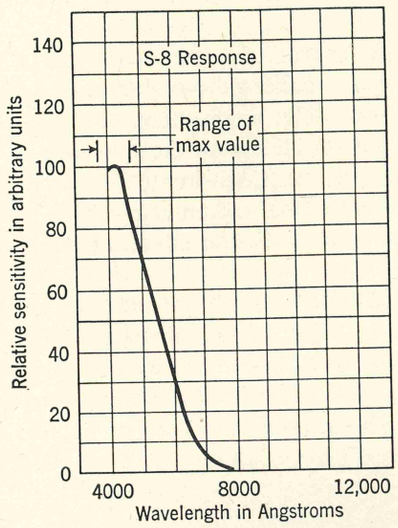
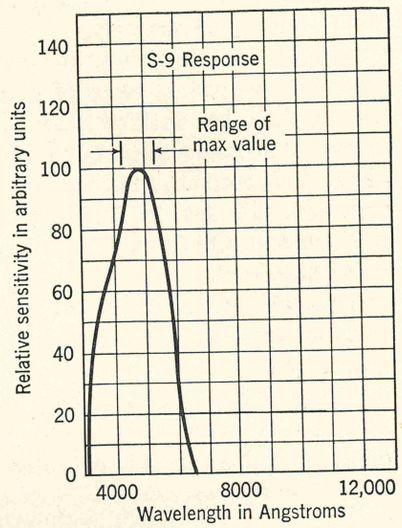


FIG. 8. Spectral response curves of various commercial phototubes. *a–d. RCA Bulletin* CRPS-102-A.





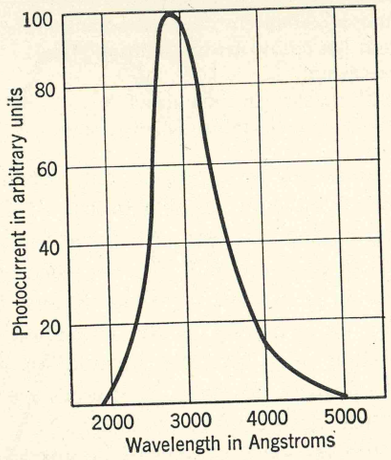


FIG. 8 (*Continued*). *e* and *f*. *RCA Bulletin* CRPS-102-A. *g*. S-6 sodium.

The spectral response curves of a number of the metallic elements sensitive mostly in the ultraviolet are shown in Fig. 7. This figure shows relative values only.

Figures 8*a* to 8*g* show the response curves of some of the more common commercial types of phototubes. Except those shown in 8*d* and 8*g* these are unsuitable for most ultraviolet applications, first, because of their lime glass bulbs which cut off all except the near ultraviolet and, secondly, because of their very high sensitivity to visible radiation. Because of the latter any stray visible radiation produces a photocurrent which may be large compared with the effect which is being measured.

The cathode surfaces used in most of these cells are not pure metals but composites whose nature is still the subject of investigation. The spectral responses of various commercial types have been identified by the Radio Tube Manufacturers Association by the designation S-1 to S-9. These designations identify specific spectral responses of phototubes rather than specific photosurfaces. The constitution of these surfaces is as follows:

S-1, silver-cesium oxide-cesium (in lime glass).
S-3, silver-rubidium oxide-rubidium (in lime glass).
S-4, antimony cesium (in lime glass).
S-5, antimony cesium (in ultraviolet-transmitting glass).
S-6, sodium (in ultraviolet-transmitting glass).
S-7, silver cesium.
S-8, bismuth cesium (in lime glass).
S-9, antimony cesium (transmission type).

The response of some of these cells in the ultraviolet may be considerable if they are enclosed in suitable bulbs. This is illustrated by Fig. 9, which shows the spectral response curve for a cell with an S-1 type of cathode, such as that shown in Fig. 8*a*, when enclosed in various types of envelopes. As is evident from the curves, the ultraviolet response shown in Fig. 8*a* is limited by the lime-glass envelope. It becomes quite large when an ultraviolet-transmitting glass or a quartz envelope is used. At present, however, such tubes are not commercially available, although they can be made specially.

Figure 10 shows the response of several commercial phototubes intended for the measurement of ultraviolet only.

There are literally hundreds of types of phototubes. However, for the most part they differ only in structural features which fit them for specific tasks. There are actually only a limited number of different types of photosensitive surfaces.

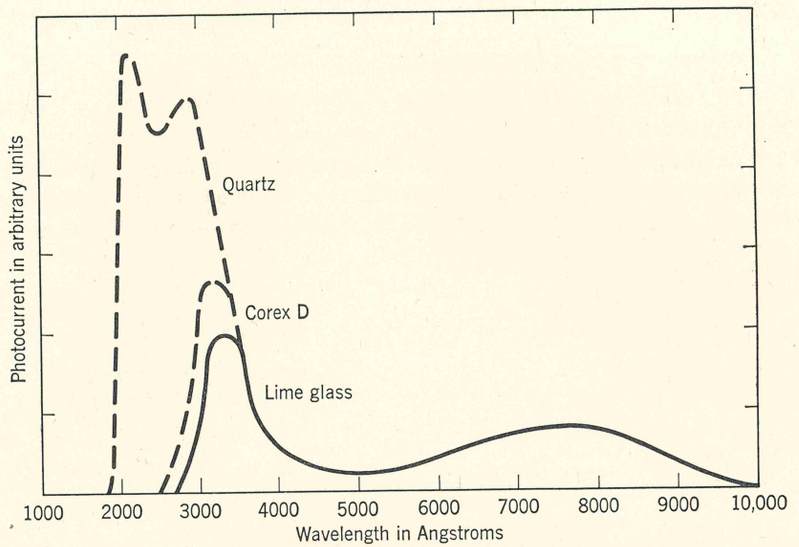


FIG. 9. Effect of envelope material on spectral response of S-1 photo surfaces. (V. K. Zworykin and E. G. Ramberg, *Photoelectricity and Its Applications,* John Wiley and Sons, New York, 1949.)

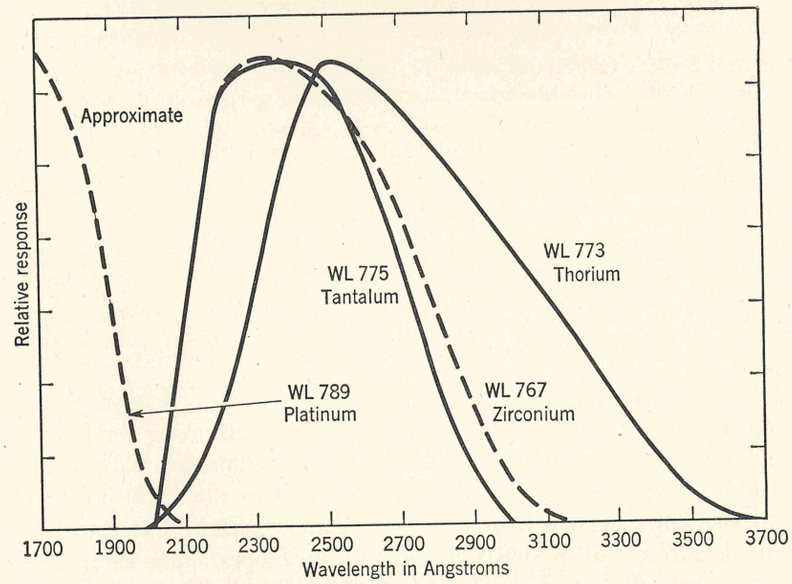


FIG. 10. Spectral response curves of some ultraviolet-sensitive phototubes. (Westinghouse Electric Corp., Data Sheet 86-080.)

Absolute Photosensitivities

The curves shown in Figs. 7–10 are in relative terms only. This is unfortunately true for most of the data given in the literature. Very few curves show absolute values. However, in the practical application of phototubes the magnitude of the current involved is of considerable moment. A few values are given in Table 3 for some of the more

TABLE 3

Absolute Values of Sensitivity *

Type	Material	Wavelength in Angstroms	Microamperes per Microwatt
S-1	Silver-cesium oxide-cesium	8000	0.002 *
S-3	Silver-rubidium oxide-rubidium	4200	0.0016 *
S-4	Antimony-cesium	4000	0.042 *
S-5	Antimony-cesium (in 971 glass)	3400	0.032 *
S-9	Antimony-cesium (transmission type)	4800	0.02 *
...	Cadmium magnesium alloy (in UV glass)	2537	0.0004 †
...	Sodium (in UV glass)	2537	0.013 †
...	Silver (in quartz)	2537	0.00006 †

* *RCA Bulletin* CRPS—102-A.
† L. R. Koller, unpublished data.

common commercially available tubes. This table gives the photocurrent in microamperes per microwatt of radiant energy incident on the phototube at some specified wavelength. With this information and the spectral energy distribution, it is possible to estimate the absolute sensitivity in any part of the spectrum. These values, however, must be considered only as approximations since there is considerable variation among phototubes of the same material, owing to differences in processing.

The efficiency of the photoelectric process is low. It is very rarely greater than a few per cent, that is, a few photoelectrons per hundred quanta. The quantum efficiencies of a few commercial photocells at various wavelengths are given in Table 4. These values do not represent the inherent sensitivities of the cathode surface but rather the cathode surfaces as modified by the glass envelopes. The table shows the number of electrons emitted per 100 incident light quanta. For most practical purposes, however, it is more convenient to express the

TABLE 4

Average Quantum Efficiencies of Photosurfaces at Various Wavelengths *

	Quantum Efficiency in Per Cent								
Type	2537 A	3400 A	4000 A	5000 A	6000 A	7000 A	8000 A	9000 A	10,000 A
922 S-1				0.10	0.19	0.29	0.31	0.22	0.08
926 S-3			0.49	0.35	0.35	0.10	0.04		
929 S-4		13	13.0	7.3	0.9				
935 S-5	10	10	7.4	3.7	0.6				
Cadmium magnesium alloy	0.2 †								
Silver	0.074 †								
Sodium	6.0 †								

* V. K. Zworykin and E. G. Ramberg, *Photoelectricity and Its Application*, John Wiley and Sons, New York, 1949, p. 466.
† L. R. Koller, unpublished data.

efficiency in terms of photocurrent per unit of incident energy as in Table 3.

The values given in Table 4 may be converted into microamperes per microwatt by multiplying by the factor $0.82 \times 10^{-6} \times$ wavelength in A. (The values in the two tables may show small discrepancies because they were taken from different sources.)

In using phototubes for measuring unresolved ultraviolet it is necessary to have some knowledge of the energy distribution of the source which is being measured in order to be able to interpret the results. The problem of measuring monochromatic radiation is relatively simple in principle. Provided that the phototube is sensitive to the radiation in question, the photocurrent is directly proportional to the intensity. Where the radiation is not monochromatic, however, the photocurrent reading may be very misleading.

For example, if the output of a quartz Uviarc is being investigated with a cadmium cell which has a response such as that shown in Fig. 7*a*, most of the response will be due to the 2537 A line. This is because the cell has only a small response to the 2967 A line and none at all to the 3129 or the very strong 3650 A line. Hence, for practical purposes the cell reading is a measure of the 2537 A line. On the other hand, if the output of the same arc is measured with a sodium-cathode phototube having a spectral response as shown in Fig. 8*g*, then a considerable part of the cell current will be due to the 3650 A line and the cell reading in the absence of other data will be ambiguous. However, if used to measure a germicidal lamp which emits 2537 A radiation almost to the exclusion of other wavelengths, either cell will give a reading

which is a measure of this radiation. Accordingly, phototube readings must be used with a reasonable understanding of their significance. In general, it is desirable to use a phototube which is insensitive outside the range of wavelengths to be measured.

Countless other combinations could be cited to illustrate the same principle. However, with a little knowledge of the phototube response and some filters, it is possible to make very satisfactory measurements.

Although the choice of photosensitive materials is relatively limited, filters may be used to modify phototube characteristics to some extent.

Photovoltaic Cell

The photovoltaic cell is the most all-round useful device for measuring radiation within the wavelength range to which it is sensitive. This type of cell operates in a fundamentally different manner from the phototube. A typical photovoltaic cell is shown schematically in Fig. 11, and a photograph is shown in Fig. 12. It consists of a thin layer

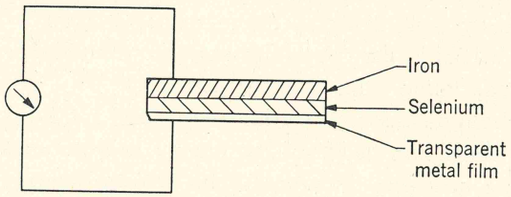


Fig. 11. Photovoltaic cell. Schematic diagram.

of selenium deposited on iron and covered with a very thin transparent layer of another metal. It owes its peculiar properties to the potential barrier between the semi-conductor (selenium) and the metal. Light falling upon the surface of the cell causes a flow of electrons from the semi-conductor to the metal. If the circuit between the two metal electrodes is closed through a meter as shown in Fig. 11, a current flows in the external circuit from the iron to the selenium. The current is directly proportional to the intensity of the incident radiation. No external emf is required. It is this feature which makes the cell so convenient for most applications and makes it possible to construct the well-known small portable photographic exposure meters. These consist merely of a very compact sensitive meter and a cell. The proportionality between current and intensity holds only for low external resistance. At very high values of external resistance the current tends to saturate with increasing light. Accordingly, it is important to use low-resistance current measuring instruments.

Practically all the commercial cells available are of the selenium type. They have superseded the copper oxide cell which was similar both in form and in function. The latter, however, is practically insensitive at wavelengths shorter than 4000 A.

The photovoltaic cell has two limitations. One is total sensitivity. It is useful only for currents which are large enough to read on a sensitive galvanometer. It cannot conveniently be used for currents so

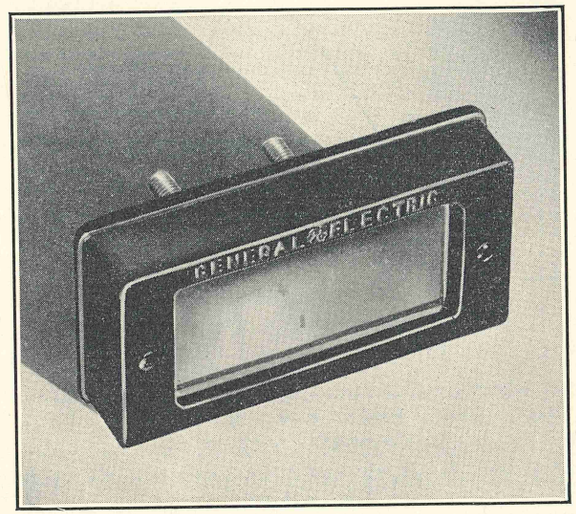


Fig. 12. A commercial photovoltaic cell. Selenium type. (Courtesy of General Electric Co.)

small that they must be amplified. This type of cell has such a low internal resistance that its use with amplifiers is not practicable. Consequently, it cannot be used for very low light intensities. This current limitation is usually not a serious one in most ultraviolet applications.

The other limitation is the spectral response of the cell, shown in Fig. 13. The cell is insensitive to wavelengths shorter than 2700 A, and its sensitivity to wavelengths in the range less than 3100 A is very low in comparison with its response to visible. Accordingly, if the cell is to be used for ultraviolet, it is necessary to filter out the longer wavelengths.

Relative Advantages of Phototubes and Photocells

Photovoltaic cells have the advantage over phototubes for ultraviolet measurement of being compact and independent of any external source

of emf. They have the disadvantage of being unsuited for measurements of very low light intensity. Only one type of spectral response is available.

Phototubes, on the other hand, may be used at extremely low light levels. A considerable number of cathode materials is available, allowing a certain amount of choice in the nature of the spectral response.

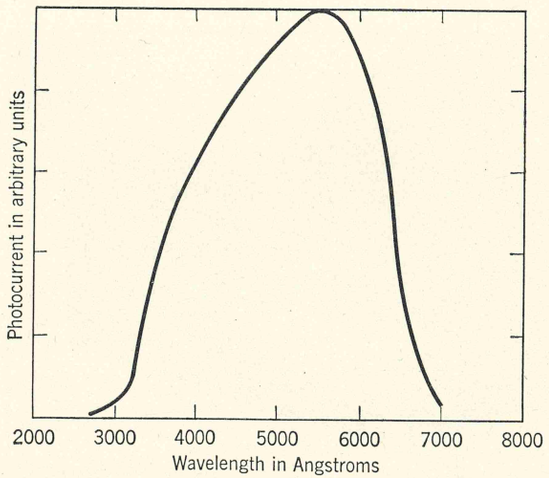


FIG. 13. Spectral response of selenium photovoltaic cell. (*Gen. Elec. Bulletin* GEA-24670.)

RADIATION CONVERTERS

Photocells which respond only to visible radiation may, nevertheless, be used for measurements of ultraviolet by means of a wavelength conversion device, such as a fluorescent substance which is excited by ultraviolet and emits visible radiation. This material may be in the form of a separate screen, or it may be an integral part of the tube. Zinc sulfide is suitable for wavelengths in the ultraviolet around 3650 A, whereas willemite responds to radiation in the region around 2537 A. Magnesium tungstate is most sensitive to about 2850 A.

A meter of this kind for measuring the 2537 A output of low-pressure mercury vapor lamps is shown schematically in Fig. 14. It consists of a thin layer of willemite sandwiched between a glass and a quartz plate and placed directly on top of the sensitive surface of a photovoltaic cell. The photocell used for this purpose is the photographic-exposure-meter type with the self-contained indicating meter. When placed with the

quartz side up, as in Fig. 14*a*, the willemite is excited to fluorescence by the ultraviolet and emits visible radiation which is directly proportional to the ultraviolet intensity. This visible radiation then results in a photocurrent which is a measure of the ultraviolet. In addition to the visible radiation from the phosphor which reaches the photocell, some visible radiation from the source also passes through the phosphor layer and the glass and quartz filters. In order to correct for this, a second

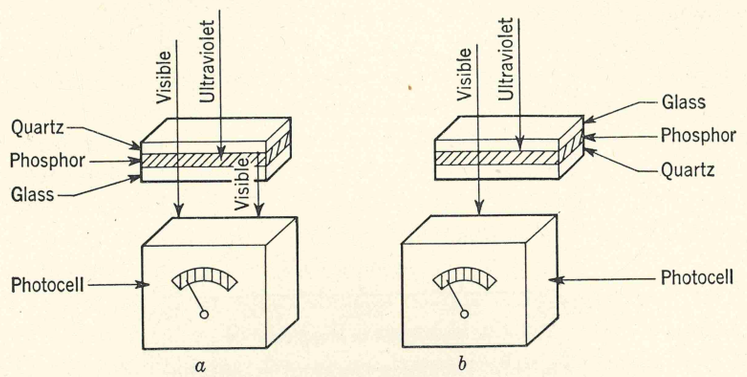


FIG. 14. Luckiesh-Taylor conversion-type ultraviolet meter.

reading is taken with the plate reversed as in Fig. 14*b*. The phosphor is not excited to fluorescence this time because the ultraviolet does not penetrate the glass. The visible radiation from the source, however, reaches the cell in the same intensity as for the first arrangement. Accordingly, the difference between these two readings represents the light from the willemite which is directly proportional to the ultraviolet.

This device is particularly well suited to the measurement of the 2537 A radiation from low-pressure mercury vapor lamps because of the high concentration of energy in this line and because of the selectivity of the willemite. Figure 15 shows the excitation curve or relative effectiveness of energy of different wavelengths in exciting $ZnSiO_4$ to fluorescence. The curve shows that the willemite is strongly excited by 2537 A but is insensitive beyond 3000 A. If a significant amount of other wavelengths which will excite the willemite is present, the photocell readings will be ambiguous.

A modification of this principle consists of a balanced pair of cells, each equipped with a filter, one of glass and one of quartz, both coated on the under side with willemite.[2] The two cells are balanced in a circuit together with a sensitive meter which reads the difference in cur-

rent between them. This device has a sensitivity of about 1 μA for an intensity of 10 μw per cm^2 of 2537 A energy.

The same principle can be used for other wavelength regions. One of the chief difficulties is to find phosphors which are excited only by a very narrow band of wavelengths. Photomultiplier tubes which are insensitive below 3000 A have been used to measure wavelengths as short as 900 A by coating the bulbs with oil which fluoresces in this region.[3]

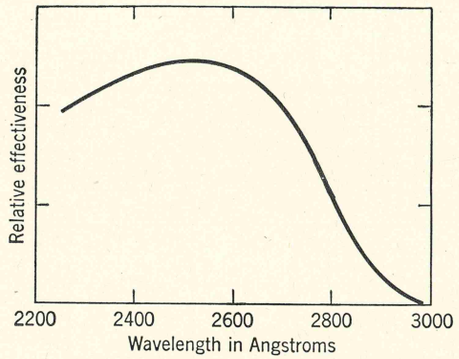


FIG. 15. Excitation spectrum of willemite.

A meter for measuring radiant energy within the narrow range of the erythemal region applies the same principle with some additional filtering.[4] A series of filters is placed in front of the phosphor which in this case is magnesium tungstate. The magnesium tungstate phosphor responds to somewhat longer wavelengths than willemite. The filters are Corning 9863 and Corning 9700. An additional set of filters consisting of methyl methacrylate, Chromex 2324, and Corning 4010 is used between the phosphor and the photocell to limit the short ultraviolet and the infrared from the source from reaching the cell. The combined effect of these filters and the spectral-response curve of the phosphor is to give an overall spectral response which is a fair approximation to the erythema curve.

PHOTOGRAPHIC PLATE

The photographic plate is the usual detector in ultraviolet spectroscopy. The degree of blackening of the plate is a measure of the radiation intensity. The measurement is made photometrically by means of some form of densitometer. Under carefully controlled conditions of exposure and development, this method is capable of a high degree of accuracy.

Ordinary photographic plates are sensitive in the region between 2200 and 5000 A. Panchromatic plates are sensitive as far in the red as 7000 A.

The gelatin of the plates is a strong absorber for ultraviolet of wavelengths shorter than 2800 A and is practically opaque for wavelengths shorter than 2000 A. One method of overcoming this difficulty is to make plates which are practically free of gelatin. A more satisfactory method is to coat the plates with a substance which fluoresces in the ultraviolet. The fluorescent radiation which is emitted is of longer wavelength than the ultraviolet and so is able to penetrate the gelatin.

A number of substances have served this purpose. One of them is ethyl carboxylic ester of dihydrocollidine. Various mineral oils [5] have also been used as well as a number of organic substances. A precise statement of photographic sensitivity requires consideration of a number of other factors. These are discussed in *Practical Spectroscopy* by Harrison and in *Photographic Plates for Scientific and Technical Use* published by the Eastman Kodak Company.

A special test paper which changes color on exposure to ultraviolet has been developed by the U. S. Bureau of Standards. This is designed specifically for calibrating carbon arc lamps used in the textile industry and other industries for testing the stability of materials to light. This test paper is made from a purified sulfite pulp and is dyed with Benzoazurine G (Color Index No. 502). After exposure to the arc, the paper is compared with a set of calibrated standards which have been exposed to a master lamp to a definite dosage. When stored in the dark these standards are colorimetrically stable over long periods. By means of this method it is possible to measure integrated exposures to the standard arc to within 10 per cent or better.[6]

CHEMICAL METHODS

The chemical devices for measuring ultraviolet consist of chemicals which undergo a visible or easily measurable change on exposure to ultraviolet. The chemical methods had the advantage of relative simplicity in the early days of the study of ultraviolet. With the development of the photovoltaic cell and advances in the electronic art, this is no longer so. The methods are slow, involving analytical procedures such as weighing and titrating. They are sensitive to temperature and to small amounts of impurities. This latter necessitates great care in the choice of reagents and makes comparisons between different experimenters or at different times difficult.

One of the most widely used chemical ultraviolet detectors has been the acetone methylene blue reaction. An aqueous solution of acetone methylene blue is bleached by ultraviolet. The solution is sensitive to wavelengths shorter than about 3200 A, and the amount of bleaching is proportional to the exposure. The solution is exposed in a small-diameter quartz tube, and the color compared with a set of standard solutions. The reaction is very slow so that for solar ultraviolet it is possible to get only an integrated value for the whole day. It reverses rapidly in the dark; hence an error is introduced in alternate cloudiness and sunshine. The results which can be obtained by means of this detector are only approximate.

Another measure of the intensity of ultraviolet is the rate of decomposition of oxalic acid in the presence of uranyl sulfate. The spectral response of this reaction extends from 4100 A to wavelengths shorter than 3132 A. The amount of decomposition is determined by titration with potassium permanganate. This is the most reliable of the photochemical detectors.

Another detector is the darkening of zinc sulfide.[7] Zinc sulfide is made into a paste saturated with lead acetate. It is darkened irreversibly by ultraviolet shorter than 3500 A. It has a maximum sensitivity at about 3132 A. The time required to darken the paste to a reflection factor of 50 per cent is inversely proportional to the ultraviolet intensity. The reflection factor is determined by a photometer or by comparison with a set of standard gray papers. In the range between 2890 and 3130 A, 1 Zns unit (reduction of reflection factor to 50 per cent) is equivalent to 720,000 ergs per cm^2.

The only commercially developed photochemical meter is the I. G. Farbenindustrie Ultraviolet Dosimeter. In this device the color sensitive material is an alcoholic solution of leuco-cyanide of a triphenylmethane dye. This solution turns pink when exposed to ultraviolet in the range between 2500 and 3300 A. In the commercial instrument the various densities of pink are reduced to a neutral gray and matched with a standard by inserting one of a set of 12 calibrated filters of different density into the optical path.

Various other compounds show color changes on exposure to ultraviolet, but none have been widely used as ultraviolet detectors. These photochemical methods are probably only of historical interest today.

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Index

Absorption, of atmosphere, 110–114
  of 2537 A by water, 224
  of ultraviolet in eye, 5
Absorption coefficient, 140, 141
  of air, 172
Absorption coefficients, of driers, 193
  of oils, 191
  of plasticizers, 192
  of resins, 191
  of thinners, 192
Acetone methylene blue ultraviolet detector, 260
Adams, E. Q., 229
A-H1 capillary lamp, 56, 57
A-H4 capillary lamp, 50
A-H5 capillary lamp, 56, 58
A-H6 capillary lamp, 53–56
A-H9 mercury arc, 56, 57
Air, disinfection of, by ultraviolet, 214; *see also* Disinfection of air
  transmission of, 171
Air mass, 108
Aluminum, reflection of, 180
American Medical Association, 13, 18, 39
Amplification of photo currents, 241, 242
Anderson, J. A., 104
Angstrom, 2
Apker, L., 75
Arc, anode material of, 29
  cyclic variation of, 71
  definition of, 21
  dynamic characteristic of, 25
  electrodes used in, 20
  enclosed, 20
Arc, instability of, 23
  low-frequency operation, 70
  open, 20
  pool-type, 35
  potential distribution in, 26
  restarting of, 70
  spectrum of, 20
  stability of, with ballast, 24
  static characteristic of, 26
  temperature of, 28
  variation with temperature and time, 36
  volt ampere characteristic of, 22
Arc carbons, for specific, *see* Carbon arc
Arc streams, temperature of various, 29
Argon glow lamps, 67
Argon in sunlamp, 42
Aston dark space, 28
Atkinson, R., 139
Atmospheric absorption, 110–114
  and scattering, 114
  transmission constant and, 112
Avogadro's number, 8
Ayrton, Mrs. H., 22

Bachem, A., 175
Bacteria, effect of humidity on, 211
  lethal dose for various, 209
  sensitivity to ultraviolet, 208
  survival ratio, 206
Bactericidal effect of ultraviolet, 205
Bactericidal effectiveness curve, 205
Ballast resistance, 23
Barnes, B. T., 42, 44, 100

Bass, A. N., 159, 161
Baum, W. A., 76
Beck arc, 79
Bemporad, formula of, for air mass, 109
Benford, F., 109, 110, 111, 132, 134, 136, 137, 190, 203
B-H4 capillary lamp, 50
B-H6 high-pressure mercury lamp, 55
Binks, Christopher, 21
BL phosphors, 234
Black, A., 204
Black body, 91
  ultraviolet from, 96
Black-light fluorescent lamps, 68, 232
  energy distribution of, 69
Black-light incandescent lamps, 101
  filtering, 101
Black-light lamp, 48
Bock, J. E., 134, 136, 137
Bolometers, 239
Brown, A., 236
Buckingham, W. D., 89
Buisson, H., 139
Bunker, J. W. M., 203
Bunsen-Roscoe reciprocity law, 208
Buttner, K., 135, 195

Calcite, transmission of, 151
Capillary-type lamps, 45; *see also* individual type numbers
Carbon arc, 77
  brilliancy of, 79
  comparison of carbons in, 89
  crater of, 77
  cyanogen bands in, 80
  effect of current of, on spectrum, 81
  effect of reflectors on, 81
  for production of vitamin D, 85
  spectrum of, 80
  spectrum summary, 86
  temperature of, 29
  temperature of crater of, 77
  with National B carbons, 83
  with National C carbons, 84
  with National E carbons, 84
  with National K carbons, 84
  with National U carbons, 85
  with Sunshine carbons, 81
Cathode, hot, 29
  overwound, 31
  separately excited, 32
Cathode dark space, 28
Cathode fall, 26
Cathode glow, 28
Cathode spot, 34
Chaney, N. K., 77
Chemical ultraviolet detectors, 259, 260
  acetone methylene blue, 260
Ch'en Shang-yi, 177
Christiansen filters, 173
Christison, F., 128
Clapp, R. H., 232
Clark, G. L., 177
Clark, J., 135, 138, 261
Click meter, 242
Cobine, J. D., 89
Coblentz, W. W., 7, 120, 121, 123, 124, 128, 129, 130, 133, 146, 156
Cold-cathode lamps, 65
Compton, K. T., 21
Conjunctivitis, 202
Copeland, P., 25
Cored carbons, 76
Corex, transmission of, 147
Corning Glass Company, 147, 148, 153
Council on Physical Medicine, 200, 217
Council of Physical Therapy, 13, 39
Crookes, W., 169
Cyanogen bands in carbon arc, 80

Daams, J., 236
Daniels, F., 139
Davy, Sir Humphry, 21
  invention of open arc by, 21
Dawson, L. D., 114, 171, 172
deGroot, W., 5
Deibert, C. R., 89
Dennison, D. M., 177
Detectors of ultraviolet, 237, 238
Disinfection, of air, 214
    fixtures for, 220
    in ducts, 216
    in rooms, 215, 217–219
  of liquids, 223
  of milk, 223
  of water, 221–223

Distribution about source, 8
Downes, A., and T. P. Blunt, 205
Dowsing, 21
Ducts, disinfection of air in, 216
Dunkelman, L., 76
Dushman, equation of, 30

Easley, M. A., 44
Eastman Kodak Company, 259
Edwards, J. D., 195
E-H4 capillary lamp, 56, 58
Einstein, A., 6
Electromagnetic radiation, 2
Electron temperature, 28
Ellis, C., and A. A. Wells, 33
Emissivity, spectral, for tungsten, 97
  total, of metals, 96
E-phosphors, 232
Erythema, 197
  dose for MPE, 199
  effect of skin condition on, 13
  evaluation of, 13
  latent period for, 199
  type of, 199
Erythemal effectiveness curve, 197
Erythemal effectiveness of various sources, 200
Erythemal equivalent, of continuous spectrum, 16
  of line spectrum, 14
  units of, 18
Erythemal flux, unit of, 13
Erythemal unit, 12
Erythemal unit of flux intensity, 14
Evaporated films, reflection from, 181
E-viton, definition of, 13
Exploded wires, 104
Exposure limits, 200
Eye, absorption of ultraviolet in, 5
  protective glasses for, 169
  visual sensitivity of average, 4

Fabri, C., 139
Falconer, R. E., 131
Faraday dark space, 28
Filters, commercial glass, 152–156
  inorganic salt solution, 159
  interference, 173
  short-wave cut-off, 159
Finkelnburg, W., 89
Finkelstein, N. A., 74, 89
Finsen, N. R., 13, 196
Fixtures for disinfection of air, 220
Flames, ultraviolet from, 104
Flaming arc, 77
Fluorescence analysis, 234
Fluorescence in eye, 6
Fluorescent lamps, 227
  black-light, 68, 69, 232
  characteristics of phosphors used in, 229
  efficiency of, 230
  energy transformations in, 231
  flicker of, 230
  ultraviolet from, 230, 231
Fluorescent sun-tan lamps, 232
Fluorite, trausmission of, 151
Forsythe, W. E., 44, 60, 97, 100, 112, 113, 122, 128, 229
Fowler, R. D., 74
Frequency and wavelength, 3
Froelich, H. C., 68, 233, 234
Fungi, killing of, by ultraviolet, 211

Gallagher, C. J., 89
Gamow, G., 139
General Electric Company, 37, 39, 40, 41, 43, 47, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 61, 62, 63, 64, 67, 69, 70, 71, 102, 212, 213, 218, 219, 220, 241, 243, 256
Germicidal effect, applications of, 213
  of ultraviolet, 205
Germicidal lamps, 60–64
  Slimline, 64
  starting circuit for, 64
Germicidal units, 18
Ginther, R. J., 232
Glass, effect of iron on transmission of, 145
  solarization of, 152, 158
  transmission of, 145
Glass filters, transmission of, 152–156
Glow lamps, 66, 67
Gotz, F. W. P., 139
Granath, L. P., 114, 171, 172
Grant, C. K., 245

Hadley, L. N., 177
Hall, H. H., 236
Hamperl, H., 236
Hanovia Chemical and Manufacturing Co., 35, 37, 38, 74
Harris, R. S., 203
Harrison, G. R., 261
Hass, G., 195
Hausser, K. W., and W. Vahle, 197, 199
Heat lamps, 99
Henschke, U., 201
Herschel, Sir William, 1
Hess, A., 202
Hewitt, Cooper, 21
High-current arc, 79
High-intensity arc, 79
High-pressure lamps, starting of, 45
High-pressure mercury lamp, 44–58
  air-cooled, 55
  continuous spectrum in, 45
  voltage gradient in, 44
  water-cooled, 53
High-pressure Xenon arc, 76
Hoffman, F., 97
Holladay, L. L., 12, 95, 103, 193, 215
Hollaender, A. E., 206, 208, 210
Hot cathodes, construction of, 31
Hours of sunshine, 131
Houtermans, F., 139
Hulburt, E. O., 107, 114, 166, 171, 172
Huldschinsky, K., 202
Hydrogen arc, 74
  energy distribution in, 74

Incandescent lamps, 97
  black light from, 101
  burn-out of, 98
  effect of operating voltage on, 102
  efficiency of, 98
  radiation from, 99–103
  summary of radiation from, 104
Incandescent radiator, 90
  energy distribution of, 92
  ultraviolet from, 94
Influenza virus, inactivation curve of, 209
Infrared, discovery of, 1
Inorganic salts, transmission of, 159
Interference filters, 173
Interference of ultraviolet, 1
International Commission on Illumination, 13
Ionization by ultraviolet, 235

Jackson, E. H., 21
Johnson, F. S., 261

Karash, W. J., 100
Kasha, M., 161, 162, 163
Keane, J. C., 236
Keating, 21
Kinsey, U. E., 236
Knowles, T., 237
Knudson, A., 203
Koller, L. R., 226, 252, 253

Lambert's law, 140
Langen, D., 236
Lens of eye, absorption by, 6
Leppelmeir, E. T., 236
Lethal exposure for *B. coli*, 18
Lethe, definition of, 18
Limited-pressure lamps, 36
Lloyd, G., 190
Long-wave limit, 244
Long-wave limits for metals, 245
Low-pressure lamps, 56–60
  effect of ambient temperature on, 66
Luckiesh, M., 43, 49, 55, 118, 119, 123, 125, 126, 127, 167, 179, 180, 188, 193, 197, 198, 200, 205, 211, 214, 215, 222, 231, 257
Ludvigh, E., 236
Lyman, T., 149

Magnesium, combustion of, 104
Marshall, A. L., 236
Maximum duration of sunshine, 131
Menzel, D. H., 139
Mercury arcs, general characteristics of, 32
  starting of, 34
Mercury lamp radiation summary, 69, 70
Mercury resonance radiation, 59
Mercury spectrum, lines in, 33

Mercury vapor detector, 234
Mercury vapor pressure, 37
Mercury vapor sunlamp, 40
Micron, 2
Milk, disinfection of, 223
Millimicron, 2
Mirrors, protection of, 187
MPE, 197

National Bureau of Standards, 165, 169, 170, 259
National Carbon Company, 78, 81, 82, 83, 84, 85, 86, 87, 88, 89
Negative glow, 28
Newton, Sir Isaac, 1
Newton's rings, 1
Noel, E. B., 46
Nordberg, M. E., 148, 158
Nottingham, W. B., 22
Noviol, transmission of, 169, 170

Organic liquids, transmission of, 160
Oster, R. H., 177
Oxalic acid ultraviolet detector, 260
Oxyacetylene flame, temperature of, 104
Ozone, absorption by, in atmosphere, 114
  distribution in atmosphere, 116
  measurement of, 226
  odor removal by, 227
  production by ultraviolet lamp, 225, 226
  properties of, 225
  toxicity of, 117, 225

Penetration of ultraviolet, 6
Pettit, E., 17, 123, 124
Phosphors, 227–230
  BL (black light), 234
  characteristics of, in fluorescent lamp, 229
  E (Erythema), 232
Photocell, 254, 255
  radiation converters, 257, 258
Photocurrents, amplification of, 241, 242
Photoelectric long-wave limit, 244
Photoflash lamps, 103
Photoflood lamps, 99
Photographic plates, 258
Photomultiplier tube, 242
Photosensitive testing paper, 259
Photosensitivity, absolute values for commercial phototubes, 252
  of metals, 246, 247
Photosurfaces, quantum efficiency of, 253
  spectral-response types, 250
Phototubes, 239
  absolute sensitivity for commercial, 252
  commercial, for ultraviolet, 251
  comparison of, with photocells, 255
  construction and operation of, 239, 240
  long-wave limit of, 244
  spectral sensitivity of, 244–251
Photovoltaic cells, *see* Photocells
Pigmentation, 200
Pinworm, killing of, by ultraviolet, 210
Planck, M., 91, 92, 93, 97, 99
Planck's distribution law, 91
Plasma, 28
Plastics, transmission of, 163, 164
Pointolite lamps, 104
Polaroid glass, transmission of, 170
Pool cathodes, 34
Positive column, 28
Prideau, G. F., 138
Protective coatings for skin, 174
Protective glasses, 169
Pyrex, transmission of, 147
  transmission of 1849 A by, 148

Quantum, unit, 7
Quartz, inhomogeneities in, 150
  transmission of, 149

Radiation, by product of discharge, 32
  variation with distance, 8
Radio sonde, 115
Radiometers, 239
Ramberg, E. G., 245, 251, 253
Rayleigh's scattering formula, 114, 172
Reciprocity law, 14, 208
Reed, C. I., 175

Reflection, Alzak aluminum, 180
from glass, 185
from ground, 194
from magnesium carbonate, 190
from magnesium oxide, 190
from metals, 178–184
from pigments, 187, 188, 189
from skin, 193
from water, 185
total internal, 186
Reflection filters, 193
Reimann, A. L., 245
Rentschler, H. C., 242, 244, 246
Resonance radiation, 59
efficiency of production of, 60
Restarting of arcs, 70
Rickets, 202
relation to erythema, 12
relative effectiveness curve, 203
Ritter, J. W., 1
Rock salt, transmission of, 151
Rodden, C. J., 236
Rohm and Haas Company, 164
RS-sunlamp, 52
angular distribution of beam in, 52
RS-4 sunlamp, 51

S-1 sunlamp, 41–44
S-4 sunlamp, 49
Sabine, J. B., 181, 182, 183, 184, 185
Sargasso Sea water, transmission of, 168
Scattering of light in atmosphere, 114
Schraub, A., 149
Schulze, R., 201
Schuman, V., 4
Schwartz, S., 190
Scott, H. S., 261
Scott, N. W., 195
Sea water, transmission of, 166
Skin, protective coatings for, 174
reflection of, 193
transmission of, 174
Sky radiation, 117
from different parts of sky, 119
ratio of, to direct radiation, 119
variation with time of day, 118
Slimline germicidal lamp, 64
Smith, A. E., 74
Smithsonian Institution, 107
Solar altitude, 109–111
Solar constant, 106
fluctuations of, 107
Solar elevation, 109-111
Solar energy distribution, 122
at Cleveland, 125
at Tucson, Ariz., 17, 124
at Washington, D. C., 123
seasonal variation, 126, 127, 128, 129
Solar energy supplied to U. S., 106
Solar radiation, daily variation of, 120
Solar spectrum, 108; *see also* Solar energy distribution
Solar ultraviolet, at high latitudes, 130
effect of altitude on, 132
effect of ozone on, 130
geographical variation, 130
ratio of, to total radiation, 121, 129
Solar zenith distance, 108
Solarium, an artificial, 138
Solarization of glass, 152
Solid angle, unit, 8
Soller, W., 189, 192
Sparing, W. H., 25
Spectra, combinations of, 11
kinds of, 9
Spectral response, effect of envelope on phototube, 250
Spectral sensitivity, of commercial phototubes, 248, 249
of metals, 246, 247
Spectrum, band, 9
continuous, 9
energy distribution in, 9
line, 9
luminescent, 11
Stair, R., 120, 121, 123, 128, 146, 169
Starkie, D., 174
Starting circuit for germicidal lamps, 64
Steenbock, H., 204
Stefan-Boltzmann law, 91, 92, 99
Steradian, definition of, 8
Sterilamps, 64
effect of temperature on, 66
Sterilization, *see* Disinfection

Stokes' law, 232
Studer, F. J., 7
Suits, C. G., 77, 89
Sun, internal pressure of, 106
temperature of, 106
Sunburn, *see* Erythema
Sunlamp, definition of, 38
erythemal effect of, 42
germicidal effect of, 42
Sunlight, artificial, 138
Sunrise, time of, 132
Sunset, time of, 132
Sunshine, incidence of, on windows, 135
maximum duration of, 131
total annual hours of, 137
Sun-tan creams, effect of, 201
Sun-tan fluorescent lamps, 232
Sun-tan oil, 174; *see also* Skin, protective coatings for
Survival ratio of bacteria, 206
Sutler, E., 135, 195

T-6 Slimline lamp, 64
Taft, E. A., 75, 150, 151
Tanning, 200
relation to erythema, 12
Taylor, A. H., 12, 193, 198, 231, 257
Temperature, of electrons in arcs, 28
of gas in arcs, 28
Thermionic emission, 30
Thin windows, 169
Thorp, C. E., 225
Tisdall, F. F., 236
Total radiation, 91
Tousey, R., 261
Transmission, 140
Transmission constant for air mass unity, 112
Transmission, of air, 171
of distilled water, 166
of inorganic salts, 159
of organic liquids, 160
of plastics, 163, 164
of quartz, 149
of Sargasso Sea water, 168
of sea water, 166
of various beverages, 171
of various foods, 171
Transmission, of water from U. S. cities, 167
see also specific materials
Transmittance factor, 140
Tucson, solar spectrum at, 16
Turner, W. E. S., 174

Uviarc, 37
energy distribution of, 38, 40
Ultraviolet, absorption of, in eye, 5
definition, 3
discovery of, 1
extreme, 3
far, 3
in therapy, 196
limits of, 3
limits of vision, 5
near, 3
penetration into skin, 6
sources of, 2
units, 7, 8
vacuum, 4
visual sensation produced by, 5
Ultraviolet barriers, 220
Ultraviolet detectors, 237, 238
Ultraviolet dosimeter, 260
Ultraviolet limit of sunshine, 134
Units, biological, 12

Vahle, W., 197, 199
Viruses, killing of, by ultraviolet, 210
Visibility curve, 5
Visible spectrum limits, 3
Vitamin D, production of, 204
Volt ampere characteristic, negative, 23
of arc, 22
of ohmic resistance, 22
Volta, A., 21
Voogd, J., 236
Vycor, transmission of, 148

Water, disinfection of, 221–223
transmission of distilled, 166
Water-cooled high-pressure lamp, 53
Wavelength, relation to frequency, 3
Wavelength units, 2
Welding arc, temperature of, 29
Wells, A. A., 31

Wells, W. F., 18, 207
Western Union Telegraph Co., 72, 73
Westinghouse Electric Corp., 65, 66
Wheatstone, C., 20
Wheeler, S. M., 236
Whitney, R. V., 245
Wilcock, D. F., 189, 192
Willemite, excitation spectrum of, 258
Willenberg, H., 97
Window glass, absorption coefficient, 146
Window glass, transmission of, 145
Worthing, A. G., 97

Xenon arc, 76

Young, Thomas, 1

Zenith distance, 108
Zernike, F., 174
Zinc sulfide ultraviolet detector, 260
Zirconium arc, 72
Zworykin, V. K., 245, 251, 253

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